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中国埃达克岩或埃达克质岩及相关金属成矿作用

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摘　要: 本文概述了近年(2003~ 2006)来中国埃达克岩或埃达克质岩及相关金属成矿作用研究的一些主要进展, 主要包括岩石的分布、分类、构造背景、成因, 以及一些相关的岩石组合、成矿、实验岩石学和动力学意义等。

关　键　词: 埃达克岩; 俯冲; 拆沉; 底侵; 铜金矿化; 中国
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Adakites or Adakitic Rocks and Associated Metal Metallogenesis in China

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Abstract: Some main advances of the studies on adakites or adakitic rocks and associated metal metallogenesis in China in recent years (during 2003~ 2006) have been briefly summarized in this paper. They include the distribution, classifications, tectonic setting, and petrogenesis of adakites or adakitic rocks, and their associated rock suites, metallogenesis, experimental petrology and important geodynamic implications.

Key words: adakite; subduction; delamination; underplating; copper-gold mineraliztion; China

埃达克岩最早于 1990 年由 Defant 和 Drummond[1] 提出, 我国学者 2000 年才开始关注埃达克岩的研究, 发表了许多有关的文章[2~4]; 2003~ 2006 年, 他们在埃达克质岩及其与铜-金成矿作用的研究方面取得了许多重要进展。

1　相关术语及分类

1.1　术语

埃达克岩最初是指由俯冲板片部分熔融形成的一套富钠的中酸性火成岩[1], 其主要地球化学特征为: $SiO_2 \geqslant 56\%$, $Al_2O_3 \geqslant 15\%$(很少低于此值), Y 和 HREE 含量低于正常岛弧火山岩(如 $Y \leqslant 18 \times 10^{-6}$, $Yb \leqslant 1.9 \times 10$), 但具有较高的 Sr(很少小于 400×10), 以及 Sr/Y($\geqslant 40$)、La/Yb($\geqslant 20$)值, 暗示石榴子石在其源区作为残留矿物相存在。

张旗等[5~7] 认为埃达克岩为一套中酸性火成岩, 其特征为亏损 HREE, 且没有负 Eu 异常, 表明应来自一个较深的、石榴子石稳定残留相的源区; 他们将埃达克岩分为 O 型和 C 型: 前者富钠, 成因与俯冲作用有关, C 型则富钾(大多数的钠含量仍然较高), 为玄武质岩浆底侵引发的加厚下地壳部分熔融的产物。王强等[8] 也将其分为两种不同成因的类型: Ⅰ型由俯冲年轻($\leqslant$25~ 30 Ma)板片熔融形成, Ⅱ型由增厚玄武质下地壳熔融形成。Chung 等[9] 和翟明国[10] 把由增厚下地壳熔融形成的中酸性火成岩称为埃达克岩。Gao 等[11] 把由拆沉下地壳熔融形成的中酸性火成岩称为埃达克岩。董申保等[12] 和 Niu[13] 则强调, 仅仅岛弧区由俯冲洋壳熔融形成的中酸性火成岩才能称为埃达克岩。

许多学者[14~20] 指出, 由增厚(或拆沉)榴辉质下

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地壳熔融形成的中酸性火成岩由于具与板片熔融形成的埃达克岩类似的元素地球化学特征, 也可以称为埃达克岩或埃达克质岩。他们认为, 不管是岛弧还是非岛弧环境环境, 只要中酸性火成岩具有与俯冲板片熔融形成的埃达克岩类似的地球化学特征, 就可以称为埃达克(质)岩[21~38]。

1.2 其它分类

除了O型和C型, 张旗等[39,40]把埃达克岩分为六类: 1) 典型的埃达克岩: 由俯冲的拉斑玄武岩或MORB熔融而成; 2) 高镁安山岩: 具高$Mg^{\#}$和Cr、Ni含量为特征; 3) TTG系列: 以高Si低Mg为特征; 4) 高钾钙碱性埃达克岩: 具高K(Na_2O/K_2O接近1)、低Mg、Cr和Ni的特征; 5) 高钾高镁埃达克岩(HKMA); 6) 超钾质埃达克岩: K/Na> 1。李承东等[41]和张旗等[40]根据Sr和Yb的含量, 将中酸性花岗岩类分为五类: 1) 高Sr低Yb型(Sr> 400×10, Yb< 2×10), 其地球化学特征类似于埃达克岩; 2) 低Sr低Yb型(Sr< 400×10, Yb< 2×10); 3) 低Sr高Yb型(Sr< 400×10, Yb> 2×10); 4) 高Sr高Yb型(Sr> 400×10, Yb> 2×10); 5) 非常低Sr高Yb型(Sr< 100×10, Yb= 2×10~ 18×10)。

2 中国埃达克(质)岩的时空分布

除广东、广西、湖南和贵州四省(区)[7]外, 中国绝大多数地区都分布有埃达克质岩, 主要位于太平洋板块和亚洲板块碰撞带、秦岭-祁连山-昆仑山造山带、青藏及中国东部地区[9,15~18,21~31,33~38,42~129]。

其时代为晚太古代(2.5 Ga)到中新世(约10 Ma)。最老的埃达克质岩见于五台杂岩体, 为晚太古代(2.5 Ga)[101]。最年轻的出现于青藏[9]。早元古代埃达克质岩分布在江西的东北部[56,57]、秦岭造山带[70]和四川西部[126]。古生代埃达克(质)岩主要分布在中亚造山带[58,59,78,80,81,88,94], 古生代-早中生代的埃达克(质)岩主要出现在秦岭-祁连山-昆仑山造山带[53,72,82,112]。新生代埃达克质岩主要见于青藏[9,23~29,54,55,74~76,84]。最近, 青藏北缘和东缘也有三叠纪埃达克质岩的报道[111,113]。中国东部的埃达克质岩主要形成于晚中生代[5~8,10,11,14~19,36,42,43,65~67,85~87,89~93,96,106]。

3 中国埃达克(质)岩的成因

3.1 构造环境和岩石组合

3.1.1 岛弧环境

(1) 埃达克岩-高镁安山岩-富铌玄武质岩组合: 新疆天山北部地区有与该区巴音沟蛇绿岩同时代的石炭纪埃达克岩-高镁安山岩-富Nb玄武质岩石组合(如阿拉套、喇嘛苏、果子沟、阿希、巴伦台-骆驼沟、土屋-延东和赤湖等)[88,94,95], 可能是俯冲的年轻且热的洋壳熔融产生的熔体交代地幔后形成的岛弧岩浆组合。准噶尔北部的泥盆纪埃达克岩-富Nb玄武岩石组合则可能与古亚洲洋俯冲有关[114,115]。赞岐岩可能与岛弧环境下的埃达克岩有成因联系[130,131]。

(2) 埃达克岩-蛇绿岩或洋中脊玄武岩: 江西东北部与同时代蛇绿岩共生的新元古埃达克质钠长花岗岩不是先前所认为的由海底扩展、洋壳剪切以及大洋岩石圈碎片的仰冲所致, 而是由大洋岩石圈的俯冲所形成[56,57]。内蒙古图林凯蛇绿岩中的埃达克岩是温都尔庙-图林凯早古生代消减带的一种岩浆岩标志[52,59]。华北克拉通的五台组基性-中性-酸性火成岩组成的晚太古代绿片岩属于洋中脊玄武岩-弧-弧后玄武岩-埃达克岩组合[101]。

(3) 埃达克岩: 中国学者认为大多数埃达克岩产自岛弧环境, 不与同时代的玄武岩或高镁安山岩共生[7,70,77,78,80,104,107,119,122,126~128]。

3.1.2 陆内伸展/挤压环境

有人认为中国东部的大多数埃达克岩与俯冲无关[7]。华北克拉通兴隆沟晚侏罗世高镁安山岩-英安岩-埃达克岩也并非在俯冲环境产生[11]。华北克拉通燕山活动地区埃达克质岩形成于190~80 Ma, 但高峰期与170~130 Ma的地壳挤压活动一致[19]。

根据中国东南部晚中生代A型花岗岩、板内基性岩、诸多断裂盆地和变质核杂带(如庐山和武功山)的分布, 人们认为扬子板块晚中生代埃达克质岩产于陆内伸展的构造背景[16,85,87,89,90]。庐枞地区(扬子地块东部)的埃达克质岩和钾玄岩可能代表了陆内伸展的构造背景[85], 与岛弧环境形成的类似岩石组合不同[1,132,133]。但也有人认为扬子地块东部在早白垩世早期处于大陆边缘岩浆弧内陆一侧, 岩浆活动与古太平洋板块的斜向俯冲作用有关[99]; 赣南的白垩纪埃达克质岩与晚中生代的岩石圈伸展和玄武质岩浆底侵有关[105]。

3.1.3 同碰撞环境

祁连造山带东南角的关山三叠纪(229±7 Ma)埃达克质花岗岩可能与华北地块和华南地块在三叠期陆陆碰撞有关[112]。

3.1.4 后碰撞环境

青藏高原新生代埃达克质岩一般晚于欧亚板块和印度板块初始碰撞的时期(70~55Ma), 被认为是后碰撞环境的产物[9,23,27,47,48,74~76,84,108]。

3.1.5 造山带伸展垮塌环境

大别造山带北部的

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早白垩世埃达克质花岗岩与同期的北大别变质核杂岩密切共生, 可能属于造山带伸展垮塌环境[85]。

3.2 岩石成因

3.2.1 俯冲洋壳的部分熔融 大部分埃达克(质)岩被认为是俯冲洋壳部分熔融的产物[12, 52, 56, 57, 59, 69, 70, 77, 78, 88, 94, 95, 103, 104, 114, 115]。江西东北部的埃达克质花岗岩是俯冲洋壳在角闪石+石榴子石稳定区低度熔融形成的[56, 57]。五台晚太古代洋中脊玄武岩-弧-弧后玄武岩-埃达克岩组合可能与类似洋中脊玄武岩的熔体和俯冲成因的熔体相互混合有关, 而洋内俯冲和与弧后盆地伸展有关的 MORB 型地幔上涌能解释这两种组分的出现[101]。

研究表明, 天山北部地区石炭纪埃达克岩-高镁安山岩-富铌玄武质岩组合可能是"埃达克质岩浆交代的岛弧岩浆岩系列"。埃达克岩最有可能由石炭纪北天山洋的年轻洋壳在俯冲过程熔融而成, 高镁安山岩可能是板片熔体与地幔楔橄榄岩相互作用的结果, 富铌玄武可能是俯冲板片熔体与少量流体交代的地幔楔橄榄岩熔融产物[88, 94, 95]。北天山早石炭纪的土屋-延东埃达克型斑岩是俯冲大洋板片的部分熔融产物[50, 121]。准噶尔北部早泥盆纪埃达克岩-富铌玄武岩的形成与古亚洲洋向南俯冲有关, 埃达克岩由俯冲的大洋玄武岩板片部分熔融而成, 富铌玄武岩来源于受埃达克质熔体交代的地幔楔的部分熔融[114, 115]。

3.2.2 滞留洋壳的部分熔融 尽管西藏东部和南部的新生代埃达克岩形成于后碰撞环境, 但有人认为它们产于老的(白垩纪前或白垩纪)滞留洋壳。侯增谦等[24]认为, 青藏高原碰撞造山带俯冲并堆积于地幔岩石圈的古老洋壳物质的变质和拆沉, 诱发了榴辉岩部分熔融, 从而产生埃达克质熔体。高永丰等[23, 48]认为西藏南部的中新世埃达克岩是滞留洋壳在后碰撞阶段部分熔融的产物, 熔体在上升过程中与上覆交代地幔楔发生作用, 使岩浆中 K 含量明显增高。通过对冈底斯铜矿带甲马、拉抗俄、南木、厅宫、冲江及洞嘎 6 个矿区含矿斑岩的全岩 Nd、Sr、Pb、O 同位素分析, 曲晓明等[74, 76]指出这些中新世含矿斑岩主要是白垩纪-古近纪俯冲到深部的雅鲁藏布江洋壳在榴辉岩相条件下的部分熔融产物, 同时有少量俯冲沉积物参与了源区混合。

考虑到江西东北部德兴的中侏罗世埃达克质斑岩和新元古(约 1000 Ma)蛇绿岩套空间上的密切关系和铌同位素的相似, Wang 等[90]指出, 除拆沉的下地壳熔融外, 其他机制(如残留在地幔的新元古俯冲洋壳的部分熔融)也可能产生这种斑岩。根据主、微量元素和 Nd-Sr-Pb 同位素地球化学研究, 李伍平[134]认为辽西北票早侏罗世兴隆沟组埃达克质火山岩可能是古亚洲洋壳残片部分熔融的产物, 熔体在上升过程中与地幔楔发生过强烈的混染作用。

3.2.3 增厚下地壳的部分熔融 大部分出现在陆内伸展/挤压、后碰撞和造山带伸展垮塌环境的埃达克质岩是由加厚下地壳的部分熔融所致[5~10, 14~16, 21, 22, 26, 28, 42, 43, 54, 84, 86, 96]。值得注意的是, 青藏高原新生代埃达克质岩也被认为是由榴辉岩质的下地壳部分熔融而成[7, 9, 26]。一些岛弧环境的埃达克质岩被认为与弧陆碰撞所导致的增厚下地壳熔融或玄武质岩浆底侵有关[53, 58, 109]。

3.2.4 拆沉下地壳的部分熔融 一些学者认为, 扬子板块东部宁镇地区的早白垩世埃达克质岩浆是由拆沉进入到下伏岩石圈地幔中的下地壳部分熔融而成[17]。而华北地块兴隆沟地区的晚侏罗纪高镁埃达克质安山岩是由古老基性下地壳拆沉进入软流圈地幔后部分熔融产生的熔体与地幔橄榄岩相互作用的结果[11]。不少人都认为一些高镁安山岩或埃达克岩是拆沉的下地壳的部分熔融所致[32, 36, 97, 135]。扬子板块东部的一些埃达克质岩石则是榴辉岩质的下地壳拆沉进入下伏热的和更塑性的岩石圈或软流圈地幔中后发生部分熔融所致[85, 87, 89, 90, 93]。

3.2.5 岩浆混合 扬子地块东部铜陵地区晚中生代一些中酸性侵入岩的地球化学特征表现出与埃达克岩相似的特点, 如高的 Na_2O、Al_2O_3、Sr 含量和 Sr/Y 和 La/Yb 值, 但其同位素迥异, 如低的 $\varepsilon_{Nd}(t)$ (-9.16~-16.55) 和高的 $(^{87}Sr/^{86}Sr)_i$ (0.7068~0.7105), 且某些样品相对埃达克岩具有高的 Y 和 Yb 含量, 很可能是幔源橄榄玄粗质岩浆和增厚玄武质下地壳岩浆混合作用的产物[15]。

3.2.6 富集岩石圈地幔的熔融 西藏东部玉龙二长花岗岩具有某些埃达克岩特征(如高 SiO_2 和 Al_2O_3, 低 MgO 含量, 亏损 Y 和 Yb, 但富集 Sr、Sr/Y 和 La/Yb 值, 以及没有 Eu 异常), 可能直接由富集岩石圈地幔的部分熔融而成[136]。也有学者认为西藏南部古近纪-新近纪埃达克质岩是板片熔体交代的上地幔熔融产物[47]。

3.2.7 地壳的同化混染和分离结晶作用(AFC)或分离结晶作用(FC) 有学者认为长江中下游白垩纪埃达克质岩是玄武岩经 AFC 过程而成[99]; 晚侏罗世-早白垩世埃达克质岩是富集地幔来源的岩浆经 FC 作用的产物[137]。

3.3 实验岩石学对岩石成因的制约

一些学者为了探讨中国埃达克质岩的成因, 总

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结了前人的实验资料, 指出中国某些高钾(相对板片来源的埃达克岩) 的埃达克质岩可能源自高压熔融(1.5~ 4.0 GPa) 或者 K_2O 含量高的变质玄武岩或榴辉岩的熔融[91]。有研究者认为控制埃达克质岩的关键是源岩、水和地壳热结构, 中国中部晚中生代富钾高 Sr/Y 值花岗岩类形成于地壳从挤压向伸展转换的环境, 可能由底侵的富碱玄武岩在 1.0~ 1.5 GPa 和 850~ 1080℃条件下发生部分熔融而成, 残留相为辉石岩类[138]。

加了2%或5%水的玄武岩在 1.0~ 2.5 GPa 和 900~ 1100°C 条件下的熔融实验[139, 140] 发现金红石在含水玄武岩的部分熔融过程中稳定的压力下限为 1.5GPa, 主要受控于水的含量和全岩成分(尤其是 TiO_2 和 K_2O), 证明 Nb 和 Ta 的分配系数 D_{Nb} 和 D_{Ta} 随水含量的增加而减小, 随着温度的降低而升高。有人认为金红石是控制太古宙 TTG 熔体 Nb-Ta 的负异常所必须的残留相[139]。根据金红石出现的最小压力(1.5 GPa) , 推测俯冲洋壳熔融形成的 TTG 的深度超过 45~ 50 km [139, 140]。

研究表明, 新生代埃达克岩的 Na_2O 含量低于 5.8%, 大约 95% 的新生代埃达克岩样品的 Na_2O 含量小于 5.0%[141]。然而, 在埃达克岩产生的压力范围(1.5~ 3.0 GPa) 内, 实验的玄武岩部分熔体大多数 Na_2O 含量超过 5.0%, 最高达到 9.0%, 这表明埃达克岩有明显的 Na 亏损现象。他们认为这是埃达克熔体在热的地幔楔中与地幔橄榄岩反应的结果。在俯冲带, 大洋板片熔融产生的埃达克熔体上升并与地幔橄榄岩发生反应, 原始的埃达克熔体获得 MgO、CaO、Cr 及 Ni 等地幔组分, 但 Na_2O、SiO_2 (还可能有 K_2O 等) 通过反应进入地幔, 导致地幔交代作用。根据长英质熔体与橄榄岩反应体系的相关系, 他们认为, 在适当的温压条件下地幔单斜辉石、橄榄石、尖晶石的混染作用以及钠质角闪石和斜方辉石的分离结晶作用, 是改变埃达克熔体组成并导致 Na 亏损的一个重要的过程。

4 成矿作用

4.1 相关的金属矿化点的空间分布

近年国内有许多与埃达克(质) 岩有关的铜金矿成矿作用的报导[7, 8, 14~ 16, 24~ 27, 34, 45, 81, 82, 85, 87, 90, 91, 95, 104, 107, 116~ 121, 128, 142~ 148], 将金、铜和银矿床[147, 148] 分为产于造山带和陆块内两大类, 再细分为若干成矿带(区) 和亚带(区)。造山带的成矿带有古亚洲洋、秦祁昆、环太平洋和新特提斯, 陆内成矿则有中国东部、青藏高原、藏东南-川西南-滇西北等成矿带。

4.2 埃达克(质) 岩成矿制约因素

已有研究表明, 制约埃达克(质) 岩成矿的关键因素在于角闪岩相向榴辉岩相转变过程发生脱水产生埃达克质岩浆, 同时萃取地幔中的成矿元素进入岩浆[147]; 埃达克(质) 岩与埃达克岩类岩石(如高镁安山岩、镁质安山岩、富铌玄武岩和高铌玄武岩等) 是多数斑岩型铜矿的容矿岩, 也是许多浅成热液矿化系统的成矿母岩, 成因上的联系可能在于埃达克质岩浆的富流体、高氧逸度和基性源岩等特征, 有利于 Cu、Au 等深源金属元素的萃取与富集成矿[142]。

藏南冈底斯斑岩铜钼成矿系统(13.6~ 16.9 Ma) 与同期埃达克质斑岩(14.5~ 17.6 Ma) 发育于大陆后碰撞地壳伸展环境, 来自深部亏损地幔物质与下地壳物质的交换, 不仅导致冈底斯加厚、下地壳熔融, 而且提供了巨量金属。同时, 在下地壳石榴角闪岩部分熔融过程中, 残留相由角闪石向石榴子石大规模转变导致角闪石的大量分解, 释放出大量流体, 是埃达克岩和斑岩铜成矿系统的主导因素[25]。然而另有观点认为, 冈底斯斑岩铜矿与雅鲁藏布俯冲板片及其上的少量洋壳沉积物混合物质部分熔融有关[74~ 76], 或与板片熔体和上地幔源区的交代作用有关[47]。

研究表明, 碰撞前的 B 型俯冲和碰撞后的 A 型俯冲相关的斑岩铜矿形成过程中, 洋壳或上地幔物质的参与至关重要, 含矿斑岩和埃达克岩可能是俯冲和交代作用的结果[143]。

有人报道了扬子地块东部的铜金矿化与晚中生代埃达克岩有关[8, 14], 并系统总结了该区铜金成矿与埃达克质岩的关系[16, 85, 87, 90, 91, 95], 指出扬子地块和大别造山带的长英质埃达克岩不是由俯冲板片熔融而成, 虽然同一区域与铜金矿化相关的镁铁质埃达克质岩具有显著的地幔特征。这表明: 1) 深部地壳熔融形成贫矿的埃达克质岩; 2) 拆沉下地壳熔融形成的熔体在穿过地幔后形成富矿的埃达克质岩。与下地壳拆沉作用有关的埃达克质岩的成矿潜力类似于俯冲环境。这表明埃达克岩浆对斑岩铜金矿床的形成有重要意义, 而勘探的构造环境却可以扩大到板内、俯冲后的环境。

除西天山阿吾拉勒山铜矿床与二叠纪增厚下地壳熔融形成的埃达克质岩有关外[124, 125], 大多数北疆地区铜金成矿与源自俯冲洋壳部分熔融形成的古生代埃达克质岩有关[7, 81, 88, 91, 94, 95, 104, 107, 119, 121]。有人认为北天山铜(金) 成矿与石炭纪埃达克岩-高镁安山(闪长) 岩-富铌玄武岩岩石组合有关[95]: 年轻

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的俯冲洋壳熔融形成的埃达克质岩浆与地幔楔橄榄岩反应, 由于俯冲板片产生的埃达克质岩浆具高氧逸度, 与地幔楔橄榄岩的强烈相互作用导致地幔中的金属硫化物分解, 成矿金属元素进入岩浆。这可能是新疆北部铜金矿化与一些埃达克岩、高镁安山(闪长)岩或富铌岛弧玄武质岩密切共生的基本原因。

5 一些地球动力学推论

(1) 与埃达克岩有关的俯冲消减、底侵和陆壳生长: 根据北天山石炭纪埃达克岩与同期巴音沟蛇绿岩有类似的 Sr-Nd 同位素组分, 有人认为它们是北天山石炭纪俯冲的年轻洋壳部分熔融的产物[88, 95]。因此, 石炭纪时北天山是岛弧而非大陆裂谷环境, 天山地区的地壳生长方式主要是侧向而不是垂向的, 且俯冲洋壳的部分熔融和亏损地幔对地壳的生长有重要贡献。北准噶尔下泥盆统埃达克岩-富铌玄武岩组合表明早泥盆世古亚洲洋壳向南对哈萨克斯坦-准噶尔板块发生俯冲[114, 115]。晚古生代新疆北部有两类埃达克岩: 分别与俯冲洋壳板片和底侵幔源玄武质岩有关[125]。根据它们的分布和与前一类埃达克岩密切相关的高镁安山岩、富铌玄武岩、苦橄岩, 认为北疆的陆壳增生方式有多样性: 既有垂直的也有测向的[125]。增生过程中有洋壳板片斜俯冲、俯冲板片撕裂、板片窗、俯冲剥蚀和玄武质物质的底侵等作用; 增生物质有俯冲洋壳板片、地幔楔、弧前棱柱、受地幔楔混染的洋壳板片熔体、地幔楔受板片熔体交代后形成熔体及底侵的幔源玄武质物质。有人认为, 赣东北俯冲洋壳熔融而成的西湾埃达克质花岗岩的 SHRIMP 锆石 U-Pb 法年龄(968 ± 23Ma) 应重新解释为洋壳俯冲的时间, 而不应该是先前所说的洋壳形成的时间[56, 57]。

(2) 埃达克质岩石与增厚的下地壳物质的拆沉作用: 由于埃达克质岩浆源于榴辉岩相, 一些研究者关注它与增厚下地壳的拆沉作用的关系[5, 6, 8, 14, 17, 71]。主要表现为: 1) 埃达克岩浆从残余的榴辉岩质源区中抽取出来是下地壳拆沉作用的先决条件[5, 6, 8, 14, 71, 86, 92, 149]; 2) 下地壳的拆沉进入下伏地幔是形成埃达克质岩浆的先决条件[11, 17, 18, 85, 87, 89, 91, 93]。

(3) 埃达克质岩与高原: 实验表明, 产生埃达克质岩浆的下地壳深度超过 40~ 50 km[140, 141, 150, 151]。基于下地壳起源埃达克质岩的成因和其他地质证据, 中国东部大陆在中-晚燕山期可能是一个高原, 到中-晚侏罗世开始隆升, 在早白垩世减薄, 高原的隆升、减薄是由陆内的造山事件和下地壳的拆沉作用的结果[5, 6]。还有学者用增厚下地壳起源的埃达克岩进一步限定了晚中生代中国东部高原的大致边界[40, 152]。

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