西太平洋俯冲带的演变:来自东北亚陆缘增生杂岩的制约

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内容提要:本文系统总结了东北亚陆缘晚古生代和中生代增生杂岩的构成与形成时代,并结合同时代火成岩组合及其时空变异以及沉积建造组合,重塑了西太平洋板块俯冲带的演变历史。结果表明:① 位于佳木斯地块东缘的跃进山杂岩代表了二叠纪俯冲带,它是古亚洲洋构造体制的产物;② 侏罗纪增生杂岩代表了侏罗纪俯冲带,与陆缘同期钙碱性火成岩组合以及含煤建造一起,共同揭示了古太平洋板块西向俯冲的开始;③ 侏罗纪增生杂岩中—晚侏罗世和早白垩世早期陆源碎屑岩物源的变化,与古地磁和生物学证据一起,共同揭示了古太平洋板块小角度斜向俯冲和东北亚陆缘走滑的构造属性,导致了低纬度侏罗纪增生杂岩向高纬度的推移;④ 白垩纪—古近纪增生杂岩与陆缘白垩纪—古近纪岩浆作用一起代表了该期俯冲带的存在,自早白垩世到晚白垩世再到古近纪岩浆作用范围向海沟方向的收缩,揭示了古太平洋板块西向俯冲以及俯冲板片后撤(rollback)过程的发生,同时标志着东亚大地幔楔的形成;⑤ 古近纪晚期—新近纪早期日本海的打开,标志着现今太平洋板块俯冲带以及东北亚大地幔楔的形成。

关键词:东北亚陆缘;晚古生代和中生代;增生杂岩;古亚洲洋体制;环太平洋体制;俯冲带演变

欧亚大陆东缘中—新生代的构造演化及其相关重大地质事件(诸如华北克拉通破坏、华南大陆的再造、深源地震、板内火山等)的发生主要受古太平洋—太平洋板块俯冲作用过程的控制(Xu Wenliang et al., 2013; Tang Jie et al., 2018; Zhu Rixiang and Xu Yigang, 2019)。然而,古太平洋板块在欧亚大陆下的俯冲演化历史以及东亚或东北亚大地幔楔形成的时间与机制却一直是固体地球科学领域争论的焦点问题之一。这些争论之所以存在追其根本原因是由于东亚陆缘缺少与大洋板块俯冲过程密切相关的直接物质记录(尤其是增生杂岩)。庆幸的是东北亚陆缘至今保存了晚古生代和中生代—古近纪早期陆缘增生杂岩,它们是重建板块俯冲历史的关键证据。因此,本文在系统总结前人对陆缘增生杂岩研究的基础上,结合同时代火成岩组合以及同时代沉积建造组合的时空变异,重塑了西太平洋俯冲带的演变历史,进而揭示了古太平洋—太平洋板块在欧亚大陆下的俯冲历史以及东亚和东北亚大地幔楔形成的时间与机制。

1 东北亚陆缘的基本构造格架和演化

在地理上,东北亚陆缘包括中国东北、俄罗斯远东、日本以及朝鲜半岛。在构造上,东北亚陆缘包括中亚造山带东段(中文文献中表述的兴蒙造山带)、华北克拉通东北缘、中国东北和俄罗斯远东中生代陆缘增生杂岩带以及日本岛弧(图1)。该区在古生代期间经历了古亚洲洋构造体制的演化——主要表现为微陆块间的拼合和古亚洲洋的最终闭合(Li Jinyi, 2006; Liu Yongjiang et al., 2017; 许文良等, 2019)。这里需要明确的是本文所指的古亚洲洋是指——位于中亚造山带东段微陆块之间的古生代洋盆均定义为古亚洲洋的范畴。在中生代期间,该区又经历了来自北西方向蒙古—鄂霍茨克构造体制和来自东部环太平洋构造体制的叠加和改造(Xu Wenliang et al., 2013; Tang Jie et al., 2018)。目前,多数学者认为古亚洲洋的最终闭合发生在中三叠世,并且是沿西拉木伦—长春—延吉缝合线自西向东呈剪刀式闭合(Wang Yini et al., 2018; Wang

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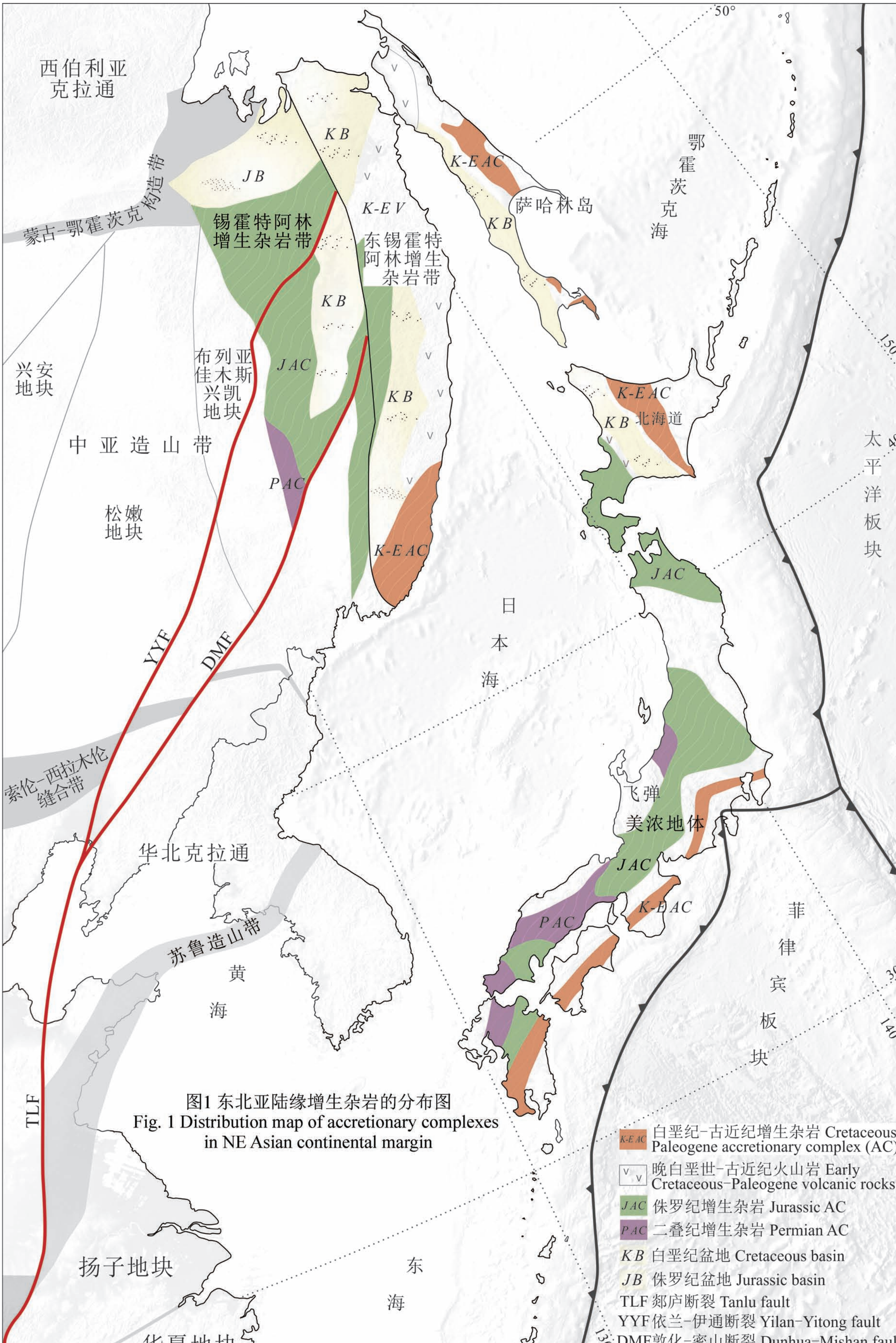

图1 东北亚陆缘增生杂岩的分布图

Fig. 1 Distribution map of accretionary complexes in NE Asian continental margin

Feng et al., 2019);少数学者认为最终闭合时间更晚,且位于儿狼山—阴山一线(吕洪波等,2018)。对于蒙古—鄂霍茨克大洋板块南向俯冲的起始时间至少可以追溯到晚二叠世(Li Yu et al., 2017),并且经历了早中生代的南向俯冲(Tang Jie et al., 2016a)、中侏罗世的闭合(李宇等,2015;Sorokin et al., 2020)和晚中生代闭合后的伸展过程(Tang Jie et al., 2018)。然而,对环太平洋构造体制的演化还存在较多争论,这主要表现在以下几个方面:

(1)古太平洋板块在欧亚大陆下俯冲的起始时间?目前主要有以下几种观点:二叠纪(Ernst et al., 2007; Yang Hao et al., 2015; Sun Mingdao et al., 2015a)、晚三叠世—早侏罗世(Wu Fuyuan et al., 2011; Zhou Jianbo et al., 2014)和早侏罗世(Yu Jiejiang et al. 2012; Xu Wenliang et al., 2013; Tang Jie et al., 2018; Guo Feng et al., 2015)。

(2)晚侏罗世—早白垩世早期古太平洋板片俯冲的形式?主要有以下 3 种观点:平板俯冲(Wu Fuyuan et al., 2019; Zheng Yongfei et al., 2018; Ma Qiang and Xu Yigang, 2021)、正常的俯冲(Zhou Xinmin et al., 2006)和小角度斜向俯冲(Tang Jie et al., 2018; Li Yu et al., 2020; Wang Yini et al., 2021)。

(3)东亚大地幔楔形成的时间与机制?目前对大地幔楔形成的时间主要有两种观点,一是认为大地幔楔形成于早白垩世晚期(Li Shuguang et al., 2017; Ma Qiang and Xu Yigang, 2021),另一种观点认为形成于古近纪(许文良等,2019),还有人认为在古太平洋和太平洋板块俯冲体系里,曾经存在两个大地幔楔——侏罗纪—白垩纪(190~90 Ma)和新生代(50~0 Ma)(Sun Pu et al., 2021);对于大地幔楔形成的机制主要有两种观点:一是认为俯冲板片后撤(rollback)(Sun Pu et al., 2021),另一种观点认为是海沟的快速后撤(Griffiths et al., 1995)。

综上所述,可以看出东北亚陆缘古生代的构造演化主要受到古亚洲洋构造体制的影响,而中生代的构造演化同时受到蒙古—鄂霍茨克构造体制和环太平洋构造体制的影响,新生代的构造演化主要受控于太平洋板块俯冲体系的影响。在不同构造体系演化过程中,尤其是大洋板块俯冲过程中往往形成陆缘增生杂岩带(杨文采,2019),它们是大洋板块俯冲体系的直接物质记录,对其物质组成和形成时代的详细解剖,是重塑俯冲带演变历史的关键(Natal'in, 1993; Maruyama, 1997)。因此,东北亚陆缘不同时代增生杂岩的存在为重建古太平洋—太平洋板块俯冲历史提供了直接证据。

2　二叠纪俯冲带:跃进山杂岩——古亚洲洋构造体制的产物

近年来,对跃进山杂岩的详细解剖,对其物质组成及其形成时代有了明确的认识,虽然部分学者仍将跃进山杂岩与饶河杂岩归于一个杂岩(晚三叠世—早侏罗世;Zhou Jianbo et al., 2014),但多数学者将二者划归为两套增生杂岩——即跃进山杂岩形成于晚石炭世—早二叠世,构造就位于晚二叠世(Bi Junhui et al., 2015, 2016; Sun Mingdao et al., 2015a),而饶河杂岩形成于侏罗纪,并经历了两次构造就位——即晚侏罗世的海山与陆缘的碰撞以及侏罗纪杂岩向北推移后的早白垩世晚期的最终构造就位(Li Yu et al., 2020)。

2.1　跃进山杂岩的构成和时代

跃进山杂岩位于佳木斯地块东缘,东邻饶河增生杂岩,呈近南北向带状展布。该杂岩由不连续出露的强变形的变沉积岩、绿片岩相变质岩、镁铁质—超镁铁质岩和花岗质岩石构成(杨金中等,1998)。镁铁质—超镁铁质火山岩主要分布在西部,而弧型辉长岩主要分布在东部,并穿切镁铁质—超镁铁质火山岩(图 2)。

跃进山杂岩中的变碎屑岩包括石英岩、石英片岩、二云母片岩和石英云母片岩,它们经历了绿片岩相变质,并且被解释为陆缘斜坡沉积(张魁武等,1997; 杨金中等,1998)。跃进山杂岩中的镁铁质—超镁铁质岩石包括典型的蛇绿岩序列——变玄武岩、辉长岩和纯橄岩、易剥橄榄岩和单斜辉石岩,个别地方产有铬铁矿(Zhou Jianbo et al., 2014)。镁铁质火山岩主要包括洋中脊型(MORB)拉斑玄武岩和洋岛型(OIB)碱性玄武岩(Bi Junhui et al., 2017)。上述蛇绿岩序列岩石被东方红辉长岩所穿切,后者的形成时代介于 274~290 Ma 之间,结合上述地质证据和辉长岩定年结果可以判定上述变玄武岩的形成时代应在 290 Ma 之前。东方红弧型辉长岩是由一套层状堆积体构成。锆石 U-Pb 定年结果表明,其中的角闪辉长岩和斜长花岗岩的形成时代分别为 290~274 Ma 和 277 Ma(Bi Junhui et al., 2015),它们均显示弧型火成岩的地球化学属性(Bi Junhui et al., 2015;Sun Mingdao et al., 2015a)。此外,东方红辉长岩中包含有大量来自陆壳的捕获锆石,揭示它们形成于大陆弧的环境,佳木斯地块东缘

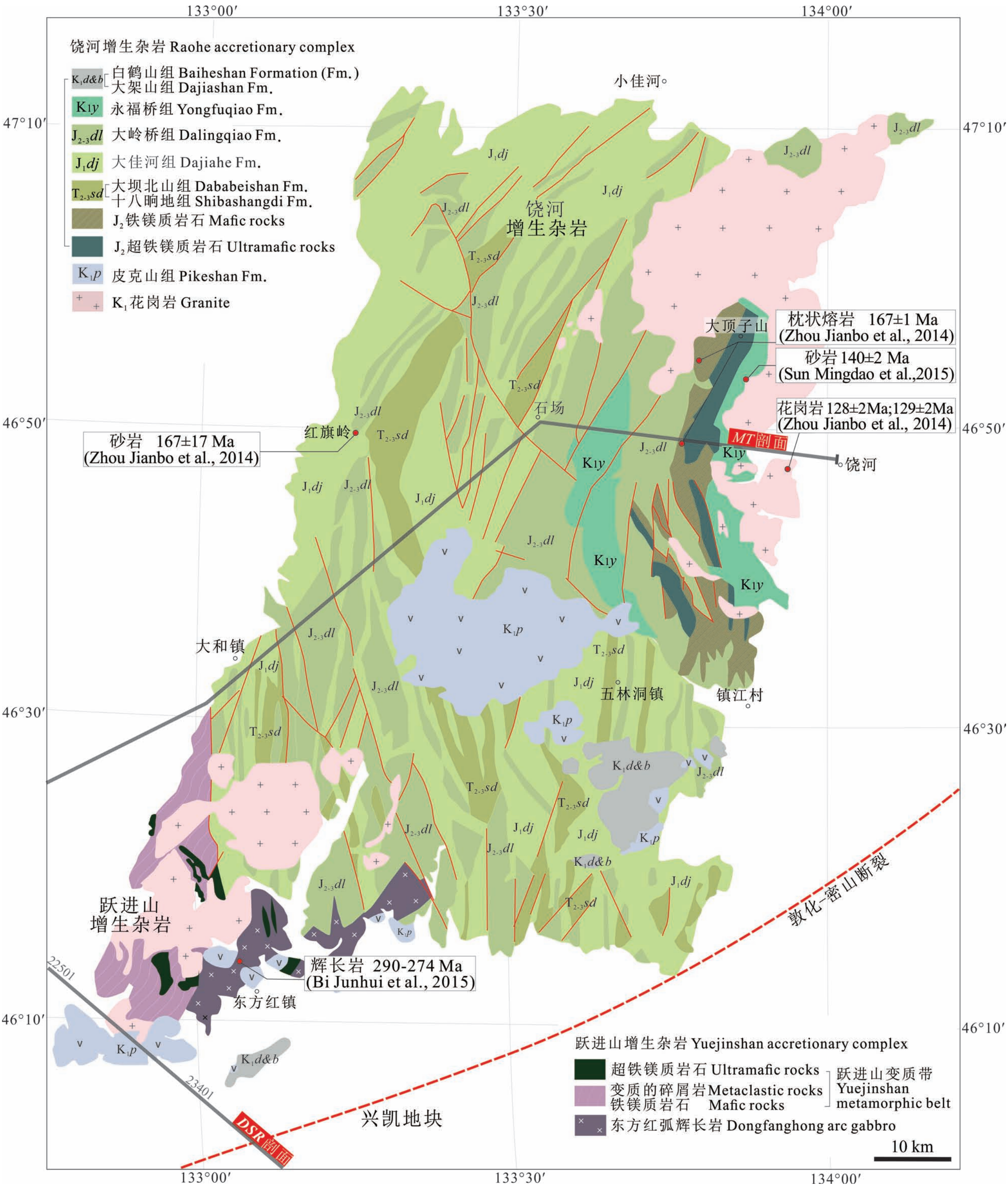

图 2 佳木斯地块东缘跃进山杂岩和饶河杂岩的分布图

Fig. 2 Distribution map of the Yuejinshan Complex and the Raohe Complex on eastern margin of the Jiamusi Block

早二叠世钙碱性火山岩组合的存在也证明了这一点（Meng En et al., 2008）。

2.2 跃进山杂岩与饶河杂岩的对比

东北亚陆缘跃进山杂岩与饶河杂岩关系的确定是揭示东北亚大陆边缘构造演化的关键。正如前述，跃进山杂岩与饶河杂岩的关系一直存在不同认识，主要表现在以下两个方面：一是二者是一个杂岩（张魁武等，1997；Zhou Jianbo et al., 2014）还是两

个杂岩(Sun Mingdao et al., 2015a; Bi Junhui et al., 2017)? 二是跃进山杂岩代表的是古亚洲洋(许文良等, 2019)还是古太平洋俯冲的产物(Bi Junhui et al., 2015; Sun Mingdao et al., 2015a; Yang Hao et al., 2015)? 两套增生杂岩的构成和时代及其变质作用特征的对比,很好地揭示了各自的形成过程及其二者的关系。

2.2.1　原岩类型和变质变形程度的对比

跃进山杂岩和饶河杂岩在岩石组合构成上具有相似的特点——除了饶河杂岩中存在石炭纪—二叠纪灰岩团块之外,它们都广泛发育镁铁质—超镁铁质火山岩和堆晶岩,尤其是具有 MORB 和 OIB 特征的枕状玄武岩以及纯橄岩、辉石岩和堆晶辉长岩;同时这些团块被陆缘碎屑岩所胶结,这些陆源碎屑岩代表了陆缘增生楔,后经与洋岛碰撞混杂形成了陆缘增生杂岩。

虽然跃进山杂岩与饶河杂岩在原岩组合上具有相似性,但二者经历了不同程度变质变形作用的改造。跃进山杂岩经历了低绿片岩相变质作用和强变形的改造(Zhou Jianbo et al., 2014),原岩为石英砂岩的变成了石英岩、原岩为 MORB 型和 OIB 型的玄武岩变成了绿片岩、原岩为泥质—粉砂质的变成了片岩;原来的橄榄岩变成了蛇纹岩(毕君辉,2018;图 3)。相反,饶河杂岩并没有经历变质变形作用的改造,地表出露新鲜的具有枕状构造的玄武岩和橄榄岩以及堆晶辉长岩(图 3)。

2.2.2　跃进山杂岩与饶河杂岩形成时代的对比

正如前述,跃进山杂岩中的镁铁质—超镁铁质火山岩被弧型辉长岩所穿切,后者的形成时代介于 290~274 Ma 之间(Bi Junhui et al., 2015),这表明跃进山杂岩形成于早二叠世之前,该杂岩的最终构造就位发生在晚二叠世,这与该区早—中三叠世沉积建造的缺乏和晚三叠世被动陆缘沉积以及晚三叠世 A 型流纹岩的存在相吻合(邵济安和唐克东, 1995; Xu Wenliang et al., 2009; Bi Junhui et al., 2015; Wang Yini et al., 2021)。

相反,饶河杂岩中除少量石炭纪—二叠纪灰岩团块外,主要形成于三叠纪—侏罗纪的深海硅质岩沉积(Kojima, 1989)、晚侏罗世 MORB 型玄武岩和堆晶辉长岩(Zhou Jianbo et al., 2014; Wang Zhihui et al., 2015)以及晚侏罗世和早白垩世早期陆源碎屑岩(Zhou Jianbo et al., 2014; Sun Mingdao et al., 2015b),它们共同被早白垩世晚期花岗岩所穿切(ca. 130 Ma; 程瑞玉等,2006; Zhou Jianbo et al., 2014),饶河杂岩最终构造就位发生在早白垩世晚期(Li Yu et al., 2020)。

综上所述,可以看出跃进山杂岩与饶河杂岩分属于两个不同时代的增生杂岩,前者代表了晚古生代晚期大洋板块俯冲形成的陆缘增生杂岩,而后者代表了中生代晚期最终构造就位的陆缘增生杂岩。

2.3　饶河杂岩之下陆壳的物质属性和跃进山杂岩形成的构造体制

跃进山杂岩和饶河杂岩分属于两个不同时代的陆缘增生杂岩,那么,饶河杂岩之下深部陆壳的物质组成是判定跃进山杂岩形成过程的关键——即跃进山杂岩是位于一个大陆边缘的一套构造混杂岩还是位于两个陆块之间的一个构造混杂岩? 前者可能代表了古太平洋板块在欧亚大陆下俯冲作用的产物,而后者代表了古亚洲洋(微陆块之间)演化的产物。

对饶河杂岩进行的大地电磁测深(MT)结果表明,饶河杂岩是一个构造推覆片体,其埋深在 2 km 左右(刘国兴等,2006a, 2006b)。饶河杂岩之下,MT 结果显示具有与佳木斯地块深部陆壳相类似的物质组成(电性结构)——即饶河杂岩之下应是一套具有佳木斯地块属性的陆壳物质,而不是新增生的岛弧地体(图 4)。这一认识也得到了穿切饶河杂岩的早白垩世晚期(约 130 Ma)S 型花岗岩的证实——即该期花岗岩是一套含堇青石花岗岩,说明岩浆源区为一套成熟陆壳物质——富铝质源岩部分熔融所成(程瑞玉等,2006),再次证明饶河杂岩之下为一个古老的微陆块,其物质组成与佳木斯地块上的夕线石榴片麻岩相类似。也就是说,跃进山杂岩应是两个微陆块之间一个古大洋板块西向俯冲作用的结果,鉴于本文的古亚洲洋定义——古生代期间位于中亚造山带东段中微陆块之间的洋盆都归于古亚洲洋的范畴,由此可以认为跃进山杂岩应是古亚洲洋构造体制的产物,而非古太平洋板块俯冲的结果。由跃进山杂岩代表的二叠纪俯冲带的存在也得到了反射地震剖面的证实(图 5;Xu Ming et al., 2017)。

3　侏罗纪俯冲带:侏罗纪增生杂岩——古太平洋板块的起始俯冲

3.1　侏罗纪陆缘增生杂岩的构成和时代:美浓、饶河、哈巴杂岩

在东北亚陆缘,侏罗纪增生杂岩保存最为完整,这不仅包括位于松嫩地块和佳木斯地块之间的黑龙江杂岩,而且也包括位于东北亚大陆边缘的日本美

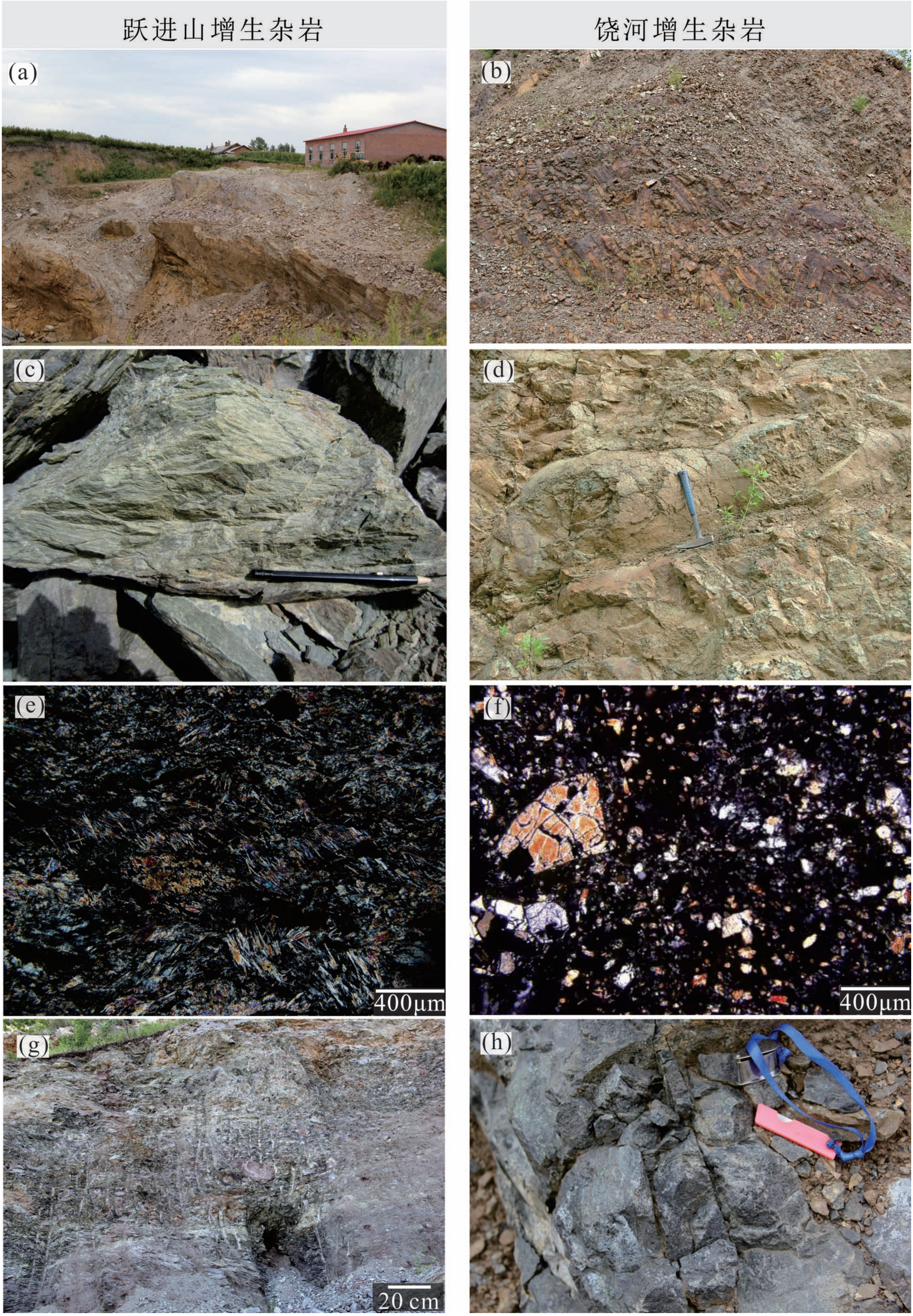
跃进山增生杂岩
饶河增生杂岩
(a)
(b)
(c)
(d)
(e)
400μm
(f)
400μm
(g)
20 cm
(h)

图 3 佳木斯地块东缘跃进山杂岩与饶河杂岩变质程度的对比:(a)石英岩;(b)硅质岩;(c)绿片岩;(d)枕状玄武岩;(e)绿片岩;(f)玄武岩;(g)蛇纹岩;(h)橄榄岩

Fig. 3 Comparison of the degree of metamorphism between the Yuejinshan Complex and the Raohe Complex on the eastern margin of the Jiamusi Block: (a) quartzite; (b) silicalite; (c) greenschist; (d) pillow basalt; (e) greenschist; (f) basalt; (g) serpentinite; (h) peridotite

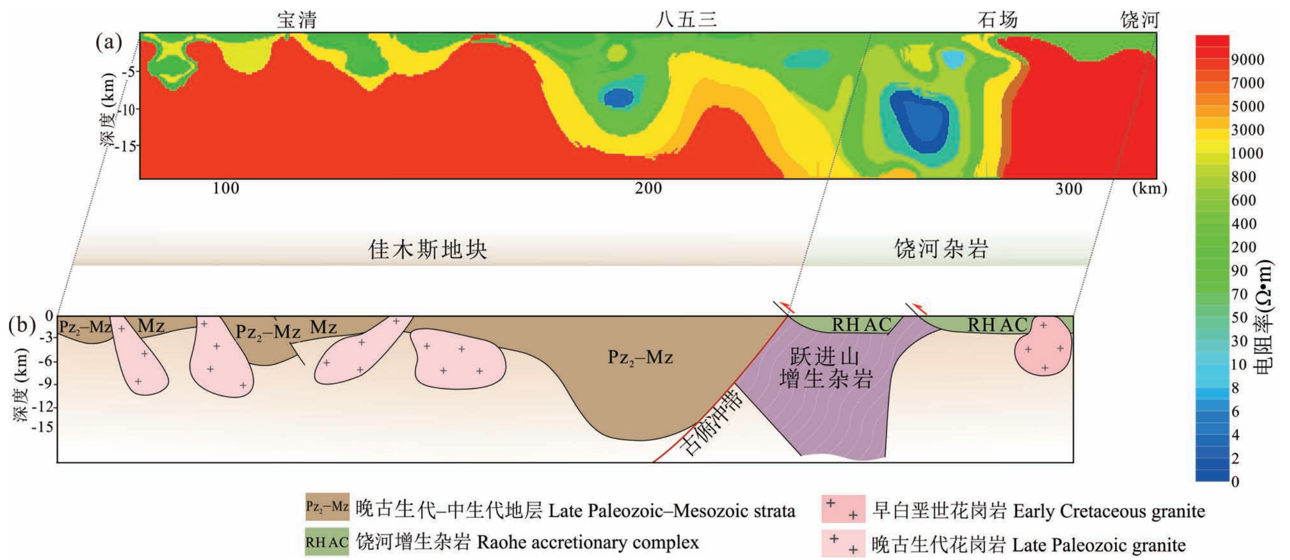

图 4 MT 揭示饶河杂岩之下深部陆壳物质组成:(a)MT 剖面二维反演;(b)MT 剖面地质解译

Fig. 4 The composition of deep continental crust beneath the Raohe Complex revealed by magnetotelluric (MT) method: (a) two-dimensional inversion of the MT profile; (b) geological interpretation of the MT profile

浓地体、俄罗斯远东的哈巴杂岩以及我国东北的饶河杂岩(图 1; Safonova et al., 2009; Safonova and Santosh, 2014)。除黑龙江杂岩位于陆内裂解的洋盆于早—中侏罗世构造就位外(Long Xinyu et al., 2020),其他陆缘增生杂岩均具有类似的岩石组合,正如前述饶河杂岩的物质组成一样,它们既包括海山阶段形成的侏罗纪枕状玄武岩和堆晶岩,也包括石炭纪—二叠纪的灰岩团块和大量三叠纪—侏罗纪的深海硅质岩沉积,并含有大量的生物化石(邵济安和唐克东, 1995; Isozaki, 1997; Zyabrev and Matsuoka, 1999)。除上述物质外,在侏罗纪杂岩中还存在作为胶结物产出的陆源碎屑岩,它们代表了陆缘增生楔,其碎屑锆石 U-Pb 年代学与 Hf 同位素组成表明,它们主要由低纬度地区侏罗纪沉积物构成(Li Yu et al., 2020)。

3.2 侏罗纪杂岩的构造就位历史和古太平洋板块的起始俯冲

侏罗纪增生杂岩中代表海山阶段的物质主要是三叠纪—侏罗纪的深海沉积物和洋岛玄武岩以及堆晶岩,其中枕状玄武岩和堆晶岩的形成时代为 167~169 Ma (Zhou Jianbo et al., 2014; Wang Zhihui et al., 2015),说明中侏罗世期间,海山还尚未达到欧亚大陆边缘。海山物质随着板块俯冲的进行,于 160 Ma 左右与欧亚大陆碰撞、并与陆缘碎屑沉积物(增生楔)相混合,构成了侏罗纪杂岩的第一次构造就位(Li Yu et al., 2020),其碰撞时间可以美浓地体约 160 Ma 的低级变质事件为证据(Isozaki, 1997)。侏罗纪增生杂岩的第一次构造就位揭示了古太平洋板块在欧亚大陆下俯冲作用的发生。这一认识也得到了黑龙江杂岩早—中侏罗世构造就位时间的支持(Zhou Jianbo et al., 2009; Dong Yu et al., 2019; Long Xinyu et al., 2020)。此外,佳木斯地块东缘早侏罗世钙碱性火山岩的发现,进一步证实古太平洋板块在欧亚大陆下俯冲作用的发生(Xu Wenliang et al., 2013; Guo Feng et al., 2015; Wang Zhihui et al., 2017; Tang Jie et al.,. 2018; Wang Feng et al., 2019)。侏罗纪俯冲带的位置一直是个争论的问题,因为目前侏罗纪增生杂岩被后期(尤其是白垩纪)构造—岩浆作用以及白垩纪增生杂岩的构造就位所改造。但是,基于佳木斯地块东缘早

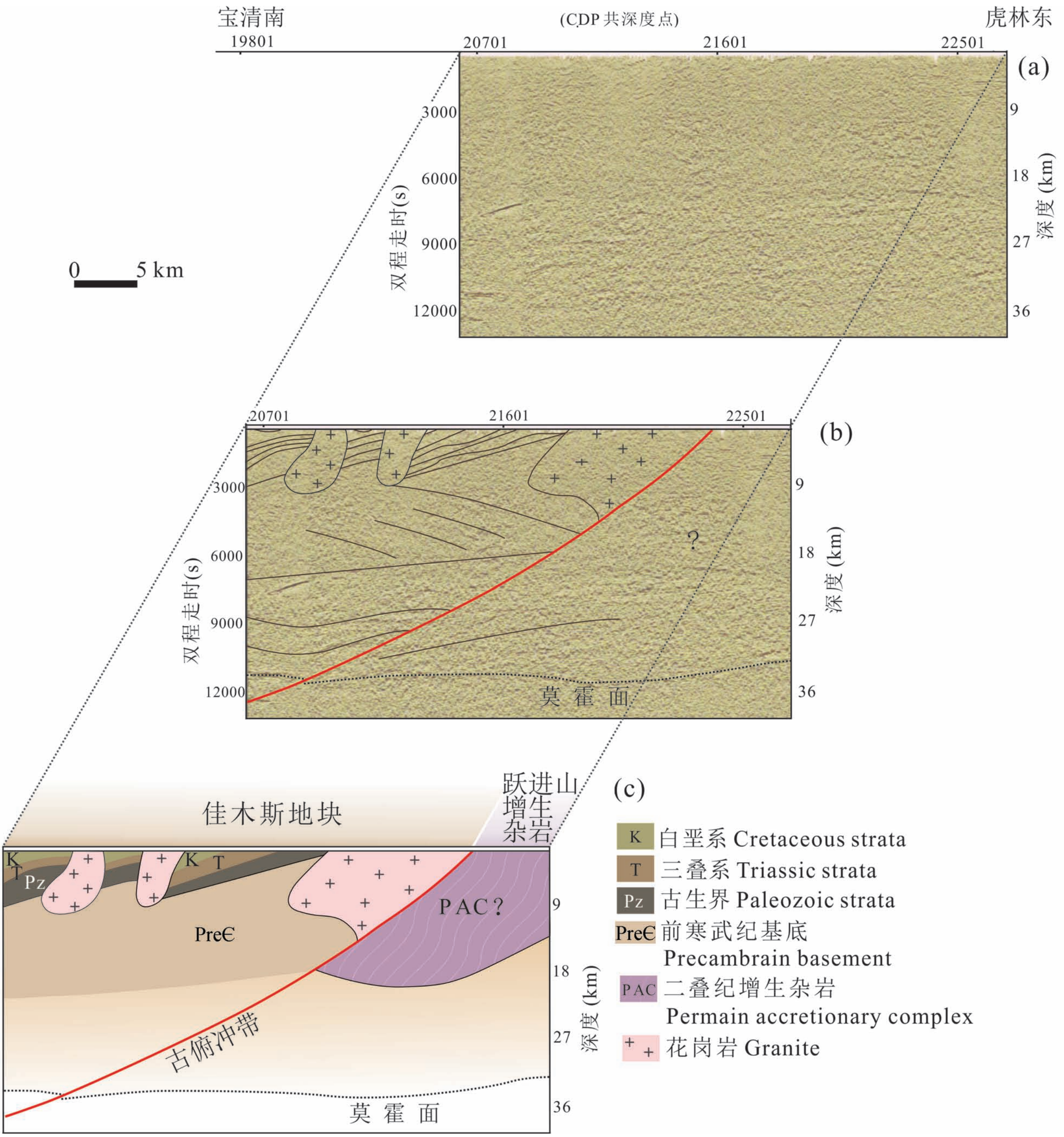

图 5 深反射地震剖面揭示的二叠纪俯冲带(引自 Xu Ming et al., 2017):(a)深反射地震剖面;(b, c)深反射剖面地质解译

Fig. 5 Permian subduction zone revealed by deep seismic reflection profile(from Xu Ming et al., 2017):(a) Deep seismic reflection profile;(b, c) geological interpretation of the deep seismic reflection profile

侏罗世钙碱性火山岩的存在,可以推断在佳木斯地块的东缘——饶河杂岩之下应该是早侏罗世俯冲带的位置。根据俄罗斯远东地质研究所早期文献记载(个人通讯,2019),在兴凯地块的东缘彼金地区曾有早侏罗世蓝片岩的报道,据此可以进一步判定,该处蓝片岩可能代表了古太平洋板块向欧亚大陆下俯冲作用发生的早侏罗世俯冲带(图 6)。

4 侏罗纪增生杂岩的北移和东北亚陆缘的走滑构造

4.1 侏罗纪增生杂岩的原始位置

侏罗纪增生杂岩中的生物组合表明该杂岩的原

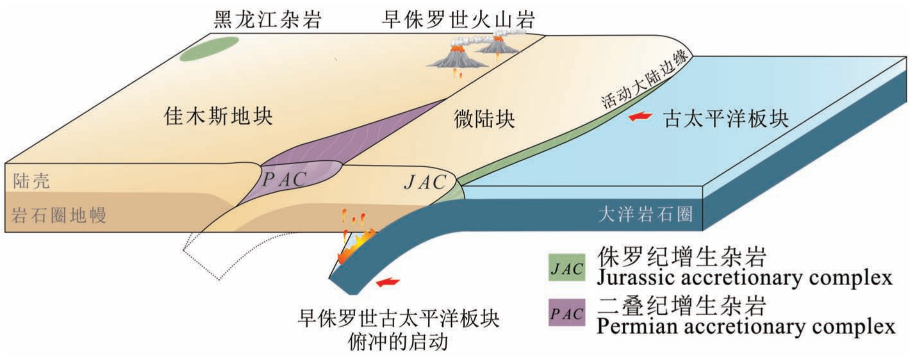

图 6 东北亚陆缘早—中侏罗世古太平洋板块的起始俯冲作用

Fig. 6 The onset of the subduction of the Paleo-Pacific Plate beneath NE Asian continental margin during the Early—Middle Jurassic

始位置处于低纬度(Kojima and Mizutani, 1987; 邵济安等, 1990; 邵济安和唐克东, 1995; Isozaki, 1997; Zyabrev and Matsuoka, 1999),而非现在的高纬度位置。这一认识也得到了古地磁研究结果的证实——即饶河侏罗纪增生杂岩的原始位置应在北纬20°左右(邵济安等,1991)。此外,作为侏罗纪增生杂岩胶结物的陆缘碎屑岩的物源研究表明,哈巴杂岩和饶河杂岩中的陆源碎屑岩具有长江中下游华南地块的物源,而日本美浓地体中陆源碎屑岩的物源则主要来自于华夏地块,它们均位于低纬度地区(Li Yu et al., 2020)。综合上述证据,可以判定,东北亚陆缘哈巴和饶河侏罗纪增生杂岩的原始位置应是位于北纬 20°的低纬度地区,而日本美浓侏罗纪杂岩的原始位置位于华夏地块的东缘(图 7a;Li Yu et al., 2020)。

4.2　侏罗纪增生杂岩的北移时间

东北亚陆缘侏罗纪增生杂岩之上又沉积有早白垩世早期的陆源沉积(如永福桥组、大架山组等),它们与晚侏罗世的沉积岩(如位于饶河杂岩西部红旗地区的大岭桥组)具有不同的沉积物源,早白垩世的陆源沉积主要为中亚造山带东部的物源(Li Yu et al., 2020)。侏罗纪杂岩中陆源碎屑岩沉积物源的变化不仅揭示了该杂岩从低纬度到高纬度平移的发生,而且限定了这一走滑事件应发生在早白垩世早期(永福桥组最年轻锆石年龄为 137 Ma;Zhou Jianbo et al., 2014; Sun Mingdao et al., 2015a)之

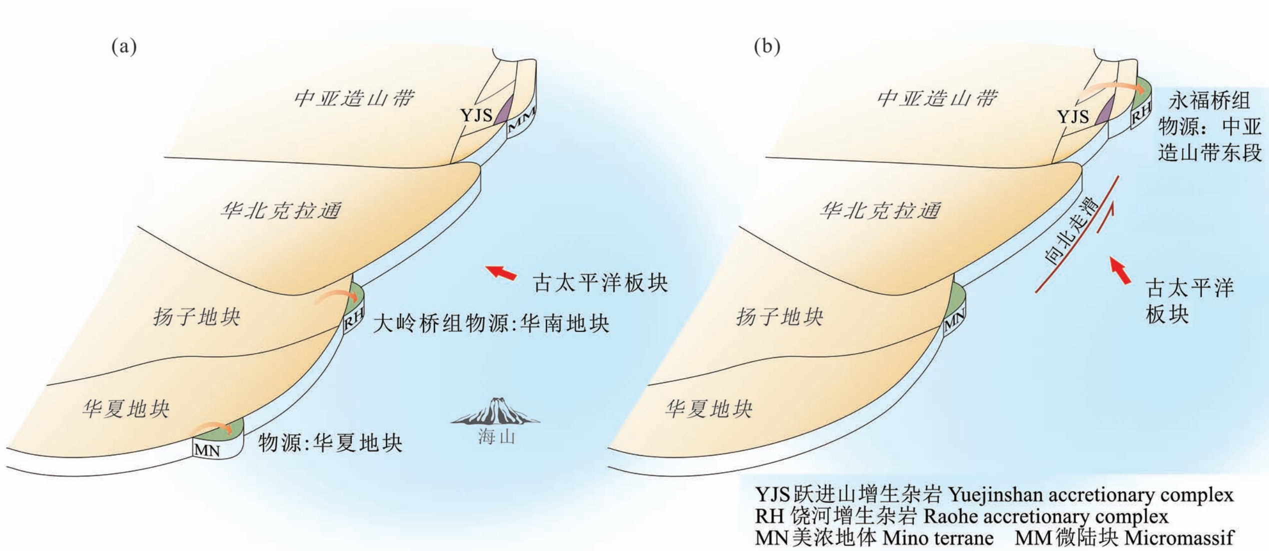

图 7 东北亚陆缘侏罗纪增生杂岩的原始位置(a)和东北亚陆缘的走滑构造(b)

Fig. 7 The original position of the Jurassic accretionary complexes in NE Asian continental margin(a) and the strike-slip structure of the NE Asian continental margin(b)

前。结合侏罗纪增生杂岩——海山与陆缘碰撞的变质时间(约 160 Ma),可以判定侏罗纪增生杂岩从低纬度到高纬度的走滑时间应介于 160~137 Ma 之间(Li Yu et al., 2020)。这一走滑时间与前人对敦化—密山断裂带研究的走滑时间相吻合(Zhu Guang et al., 2009, 2010; Utkin, 2012)。这一走滑事件的发生与古太平洋板块小角度斜向俯冲有关,东北亚陆缘(包括中国东北东部、俄罗斯远东、日本和朝鲜半岛)晚侏罗世—早白垩世早期(160~135 Ma)岩浆作用的缺乏也进一步证明东北亚陆缘走滑的构造属性和古太平洋板块小角度斜向俯冲的发生(图 7b; Xu Wenliang et al., 2013; Tang Jie et al., 2018)。

5 白垩纪—古近纪俯冲带:白垩纪—古近纪早期增生杂岩——古太平洋板块俯冲和后撤

5.1 侏罗纪杂岩的二次构造就位和古太平洋板块的西向俯冲

侏罗纪增生杂岩向北平移到现在的纬度位置(约北纬 40°)后,又沉积了早白垩世早期的沉积建造,这些沉积建造与侏罗纪增生杂岩一起发生了相同的构造变形,表明侏罗纪杂岩二次构造就位的发生,这也证明古太平洋板块西向俯冲作用的发生,这一过程也得到了东北亚陆缘约 130 Ma 钙碱性火山岩形成的印证(Xu Wenliang et al., 2013)。因此,东北亚陆缘白垩纪陆缘增生杂岩的形成更好地证明了古太平洋板块向欧亚大陆下俯冲作用的发生(Safonova and Santosh, 2014)。

5.2 白垩纪—古近纪岩浆作用范围的向东收缩和俯冲板片后撤过程

在东北亚(乃至东亚)陆缘,130 Ma 左右的岩浆作用呈带状平行陆缘广泛分布,陆缘显示钙碱性火成岩组合,而陆内具有双峰式火成岩组合特征,它们共同揭示了古太平洋板块在欧亚大陆下俯冲作用的发生(Xu Wenliang et al., 2013; Tang Jie et al., 2018)。然而,自陆内向陆缘,随着岩浆作用时代的变新(130 Ma—110 Ma—90 Ma—古近纪),岩浆作用的空间范围向东收缩(Xu Wenliang et al., 2013; Tang Jie et al., 2018),岩浆作用范围的向东收缩揭示了古太平洋俯冲板片后撤过程的发生。

5.3 东亚大地幔楔的形成时间和机制

假如以 135 Ma 作为古太平洋板块西(正)向俯冲的起始时间,依据现代滞留板片的时间估算(目前滞留在地幔过渡带的大洋板片年龄约是 30 Ma; Lai Yujing et al., 2019),可以判定古太平洋俯冲板片在大约 105 Ma 左右的时间可以到达陆内约 1000 km 左右的地幔过渡带,这与中生代晚期阜新玄武岩所具有低 δ^{26}Mg 值的特征相吻合,后者反映了再循环沉积碳酸盐对地幔的改造过程(Li Shuguang et al., 2017)。上述事实都表明,中生代晚期在东亚陆缘形成了一个大地幔楔——我们将其为东亚大地幔楔。

东亚大地幔楔的形成已经得到相关玄武岩地球化学研究的证实。那么,东亚大地幔楔的形成机制如何?这可从岩浆作用的空间变化以及欧亚大陆周边地质事件的发生得到回答。首先,从东亚陆缘岩浆作用的空间变化可知,从早白垩世晚期到古近纪,岩浆作用范围的自陆内向陆缘的收缩,揭示了俯冲板片后撤过程的发生(Xu Wenliang et al., 2013; Tang Jie et al., 2018)——也就是说俯冲板片后撤可能是形成东亚大地幔楔的主导机制。然而,地球动力学模拟结果表明,仅仅依靠板片后撤还不足以导致大地幔楔的形成,海沟的快速后撤应是导致大地幔楔形成的关键(Griffiths et al., 1995)。其次,古太平洋板块在白垩纪早期正向俯冲于欧亚大陆之下发生的时间,恰恰是大西洋北部初始打开的时间(Seton et al., 2012; Barbarand et al., 2021),随着大西洋的快速打开,欧亚大陆快速东移,欧亚大陆的向东推移导致了俯冲带东移和俯冲板片后撤滞留的发生。综上所述,可以认为东亚大地幔楔形成的机制应是欧亚大陆快速东移和板片后撤共同作用的结果。

5.4 白垩纪—古近纪俯冲带的位置

东北亚陆缘白垩纪—古近纪俯冲带的位置可以通过白垩纪—古近纪的俯冲增生杂岩、因板块俯冲作用产生的高 *P/T* 值变质带的分布以及同时代岩浆弧的分布得到制约。首先,在东北亚陆缘的东部边缘沿日本北海道的日高山脉和俄罗斯远东萨哈林群岛的中部存在一条近南北向展布的白垩纪—古近纪早期的增生杂岩带,它代表了日本海打开之前白垩纪—古近纪俯冲带的位置(Kimura,1994; 图 8)。其次,在该增生杂岩的西侧分布一条近南北展布的高 *P/T* 变质带(Liao Jiaping et al., 2018),代表了其东侧古太平洋板块西向俯冲作用的发生。第三,在俄罗斯远东的东锡霍特阿林广泛分布晚白垩世—古近纪具有弧型火成岩地球化学属性的火山岩和同时代的花岗岩(Xu Wenliang et al., 2013; Jahn Bor-

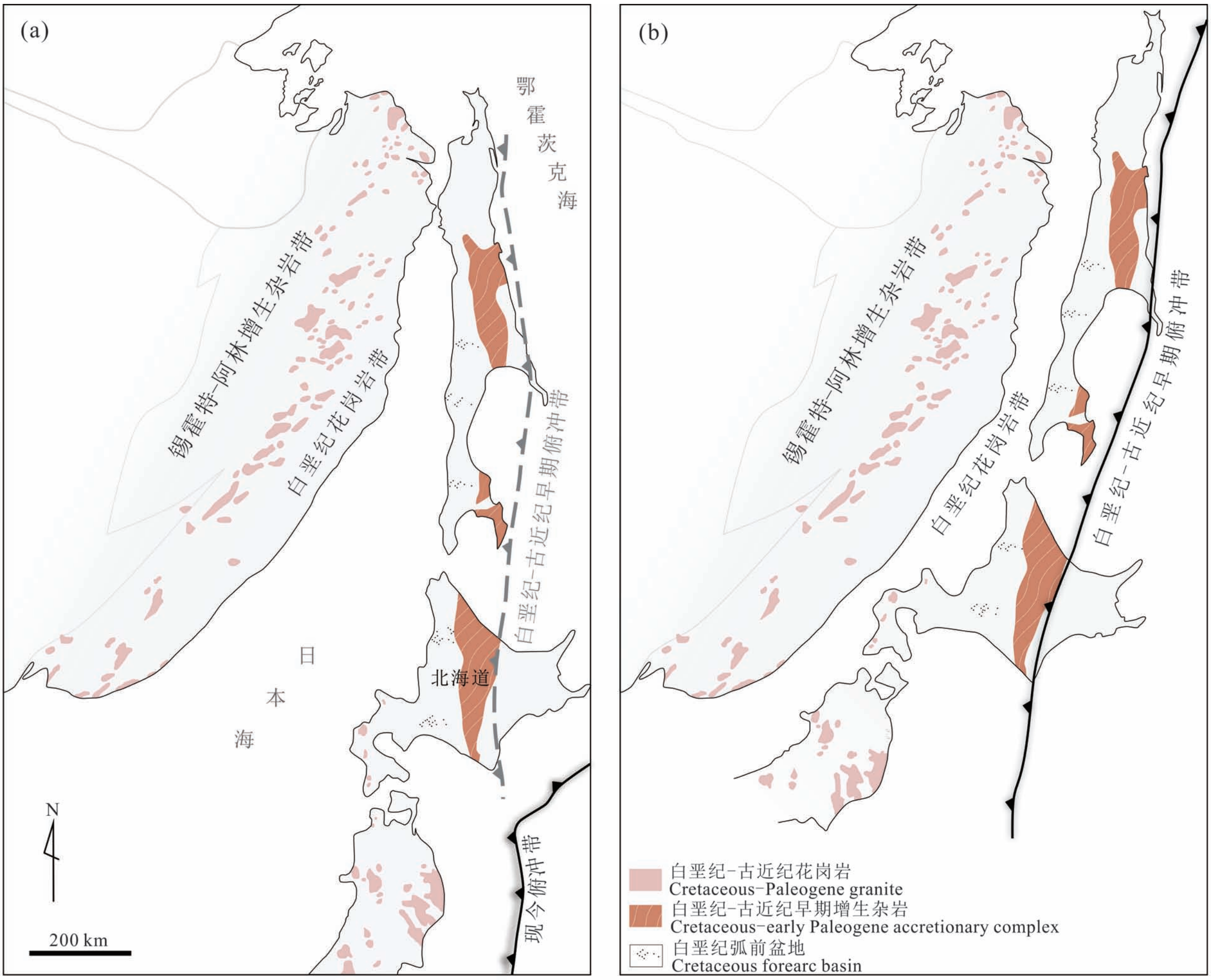

图 8 西北太平洋边缘现今(a)和古近纪早期(b)白垩纪—古近纪俯冲带的位置(据 Kimura, 1994)

Fig. 8 The present(a) and early Paleogene(b) position of the Cretaceous—Paleogene subduction zone along the northwest Pacific Ocean margin (after Kimura, 1994)

ming et al., 2014, 2015; Tang Jie et al., 2016b, 2018),它们平行陆缘和陆缘增生杂岩带分布,进一步揭示了白垩纪—古近纪早期俯冲带的存在。

6　现今西太平洋板块俯冲带:古近纪晚期日本海打开和东北亚大地幔楔形成

现代地球物理测深、深源地震和现代火山喷发等研究成果都很好地限定了现今西太平洋板块俯冲带的位置(强祖基和张立人,1983;图 1),那么,现今俯冲带是何时形成的?这还要追溯日本海的打开历史,是日本海的打开才形成了现今西太平洋板块俯冲带。

6.1　日本海打开的时间与机制

日本海打开的时间一直是个争论的问题,根据已有的地质和地球物理学研究资料,对日本海打开时间的认识其跨度可达侏罗纪—新生代早期。结合有限的海底岩石年龄测定和地磁异常的分析,认为日本海的扩张发生于白垩纪末期至新生代早期(Fukuma et al., 1998; Baba et al., 2007)。利用热流数据计算得到日本海的打开大致开始于 20 Ma 之前(Lallemand and Jolivet, 1985)。Kaneoka 等(1992)基于日本海域放射性年代学的数据,并结合古地磁资料,推测日本海的形成时间为 17~25 Ma。Tamaki (1995) 认为日本海的形成始于古日本岛弧的地壳减薄及扩张,且初始岛弧扩张始于 30 Ma 之前,初始的海底扩张则发生于约 28 Ma,至 18 Ma 时

停止,并形成了日本盆地典型的洋壳。近年来,随着日本北海道日高山脉麻粒岩相变质作用的研究,认为约 37 Ma 中压型变质作用与太平洋板块的西向俯冲作用有关,而约 19 Ma 麻粒岩相变质作用的发生,与镁铁质岩浆作用一起,共同揭示了日本海的打开(Kemp et al., 2007)。此外,对东北亚陆缘新生代玄武质岩浆源区性质随着时间的演化揭示日本海的打开时间应在 20 Ma 左右(Xiong Shuai et al., 2021)。综上所述,可以判定日本海的打开时间应在 24~19 Ma 之间(Zhang Jinrui et al., 2021)。

日本海打开的机制同样是一个存在较大争论的问题。早期在研究弧后盆地成因时曾提出弧后板块后撤机制——即弧后扩张主要是由上覆板块(即弧后板块)向陆地一侧后撤引起的(Chase, 1978; Uyeda and Kanamori, 1979)。Molnar 等(1978)基于弧后盆地演化、Seno 等(1984)基于动力学模拟,并结合当地的地质学、地层学和生物化石等资料提出了“海沟后撤”模型——即海沟后撤导致日本海的打开。近年来,随着对东北亚陆缘新生代玄武岩成分时空变异的研究表明,俯冲板片后撤与海沟后撤一起共同制约了东北亚陆缘边缘海盆地的打开(Xiong Shuai et al., 2021)。

6.2 东北亚大地幔楔形成的时间和机制

东北亚大陆边缘的演化经历了古太平洋板块俯冲和太平洋板块的俯冲以及二者之间洋脊俯冲作用的发生。正如前述,中生代晚期古太平洋俯冲板块的后撤和大西洋打开导致的欧亚大陆的快速东移导致了东亚大地幔楔的形成。随着古太平洋和太平洋之间洋脊俯冲作用的发生(通常认为该事件发生在 50~55 Ma 之间; Guo Feng et al., 2007; Tang Jie et al., 2018; Wu Jeremy Tsung-Jui and Wu Jonny, 2019)和太平洋板块在欧亚大陆下约 52 Ma 起始俯冲作用的发生(Sun Weidong et al., 2020),自此开始了太平洋板块俯冲历史。需要说明的是,在太平洋板块起始俯冲作用发生的几乎同时,形成了菲律宾板块的雏形(Deschamps, 2002),由于菲律宾板块的形成,导致现今太平洋板块俯冲方向发生了变化——即由原来的西向俯冲,转向北西方向俯冲,其空间范围只限于东北亚,因此,本文将由太平洋板块俯冲形成的大地幔楔称其为东北亚大地幔楔,它在形成时间与机制上不同于东亚大地幔楔。

首先,东北亚大地幔楔的形成时间可以从日本海的打开时间以及现代滞留板片的估算年龄得到制约。基于最新的东北亚大陆边缘新生代玄武岩成分时空变异的研究(Xiong Shuai et al., 2021)以及日本北海道日高山脉麻粒岩两期(37 Ma 中压型和 19 Ma 麻粒岩相)变质事件的研究(Kemp et al., 2007; Zhang Jinrui et al., 2021),可以判定日本海打开的时间发生在 24~19 Ma 之间,这一时间基本上代表了东北亚大地幔楔形成的时间。这一认识与现今滞留板块的估计年龄相吻合——即现在滞留在地幔过渡带的太平洋板块的年龄约为 30 Ma(Lai Yujing et al., 2019)。依据太平洋板块俯冲的起始时间约为 50 Ma,那么按照现今滞留板块年龄推算,到约 20

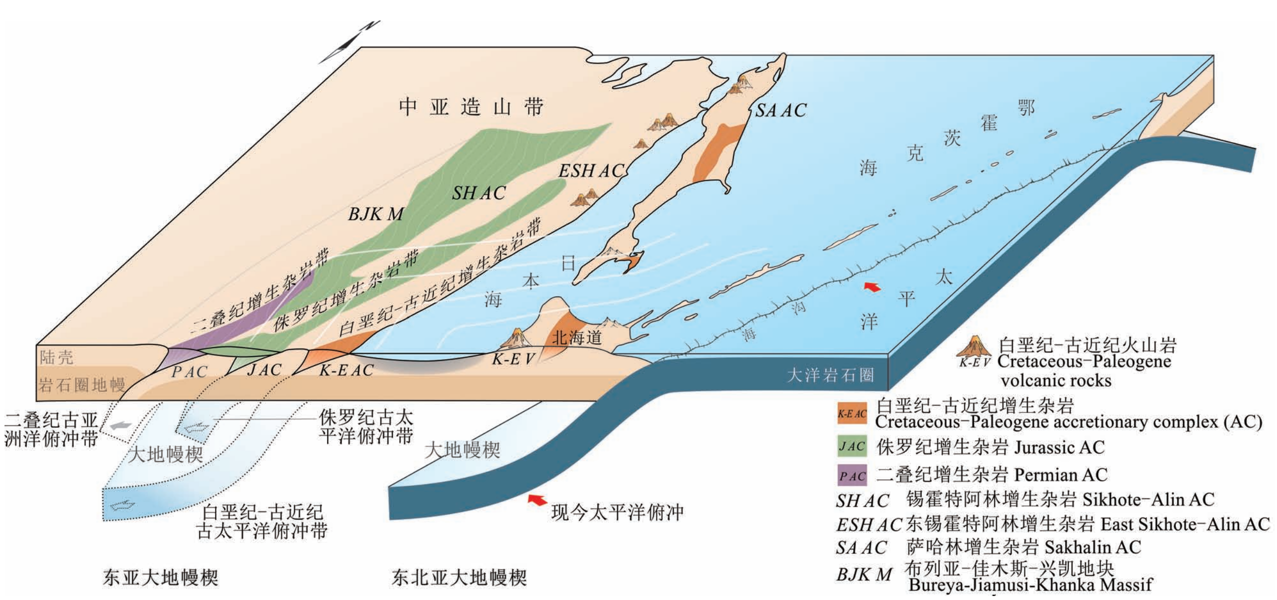

图 9 东北亚陆缘晚古生代晚期—新生代俯冲带演变模式图

Fig. 9 The evolution of the late Late Paleozoic—Mesozoic subduction zones in the NE Asian continental margin

Ma 前,起始俯冲的太平洋板块将滞留在地幔过渡带,从而形成东北亚大地幔楔(Xu Wenliang et al., 2021)。因此,综合上述研究可以判定,东北亚大地幔楔的形成时间应在 20 Ma 左右。

其次,关于东北亚大地幔楔形成的机制,虽然目前还存在争论,但最新的研究成果揭示太平洋俯冲板块的后撤(rollback)和海沟的后撤(retreating)一起共同制约了日本海的打开,我们认为这也是东北亚大地幔楔的形成机制(Xiong Shuai et al., 2021)。

综上所述,可以得出,东北亚大地幔楔形成的时间在 20 Ma 左右,而俯冲板片后撤与海沟后撤一起共同导致了东北亚大地幔楔的形成(图 9)。

7　结论

本文在综合前人研究成果的基础上,对西太平洋俯冲带演变历史进行了系统总结,得出如下结论:

(1)佳木斯地块东缘跃进山杂岩代表了二叠纪俯冲带,它是古亚洲洋构造体制的产物,而非代表古太平洋板块的起始俯冲。

(2)侏罗纪增生杂岩的形成代表了侏罗纪俯冲带的存在,并揭示了古太平洋板块向欧亚大陆下的起始俯冲发生在早侏罗世。

(3)侏罗纪增生杂岩的构造就位历史及其陆源碎屑岩的物源变化,与古地磁和生物学证据一起,共同揭示晚侏罗世—早白垩世早期古太平洋板块小角度斜向俯冲和东北亚陆缘的走滑构造属性。

(4)白垩纪—古近纪早期增生杂岩与同时期的高 P/T 变质带和陆缘白垩纪—古近纪弧岩浆作用一起,共同揭示了白垩纪—古近纪俯冲带的存在。而白垩纪—古近纪岩浆作用范围向海沟方向的收缩,揭示了古太平洋板块西向俯冲以及俯冲板片后撤(rollback)过程的发生,同时标志着东亚大地幔楔的形成。

(5)古近纪晚期—新近纪早期日本海的打开,标志着现今太平洋板块俯冲带以及东北亚大地幔楔的形成。

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Evolution of western Pacific subduction zones: Constraints from accretionary complexes in NE Asian continental margin

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Abstract: This paper systematically summarizes recent achievements in fossil accretionary complex studies in NE Asia, together with analysis of spatial—temporal variations of the coeval igneous rock association and sedimentary formations in NE Asia, with the aim of understanding the evolutionary history of the western Pacific subduction zones in NE Asia. The results indicate that: ① the Yuejinshan accretionary complex represents the Permian subduction zone in the eastern Jiamusi Massif, and resulted from the evolution of the Paleo-Asian Oceanic regime; ② Jurassic accretionary complex represents the Jurassic subduction zone in NE Asia, and together with the coeval calc—alkaline volcanic rocks, reveals the subduction onset of the Paleo-Pacific plate beneath the Eurasia; ③ provenance variations of terrigenous clastic rocks within the Jurassic complexes, together with paleomagnetic and biological data, indicate that a small angle of oblique subduction of the Paleo-Pacific plate and strike-slip tectonics took place in NE Asian continental margin, resulting in northward movement of the Jurassic complexes from low-altitude to high-altitude; ④ Cretaceous—Paleogene accretionary complex represents Cretaceous—Paleogene subduction zone in NE Asia. Toward trench contracting of extents of the Cretaceous—Paleogene magmatisms reveals the westward subduction of the Paleo-Pacific plate and rollback of the subducted slab, and marks the formation of the eastern Asian big mantle wedge; and ⑤ the opening of the Japan Sea at the end of Paleogene and early stage of Neogene marks the formation of the present Pacific subduction zone and the northeastern Asian big mantle wedge.

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