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南极煤系地层特征及其对冈瓦纳大陆裂解的启示

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摘 要:南极的煤系地层资源潜力巨大但研究十分有限。目前已发现的煤系地层主要为二叠纪地层,少量中、新生代地层,基本分布于横贯南极山脉及东南极查尔斯王子山脉地区,部分见于西南极。横贯南极山脉富煤地层主要为贝肯超群的二叠纪-三叠纪维多利亚群,查尔斯王子山脉富煤地层主要为埃默里群的二叠纪贝恩梅达特煤系。南极的煤具有高热阶特征,多为热变质煤。横贯南极山脉区域的煤多为无烟煤、超无烟煤或天然焦炭,具有高蚀变特征;查尔斯王子山脉区域的煤具有高挥发分低硫特征,贝恩梅达特煤系地层内随地层时代由老到新,代表煤系地层成熟度的镜质体反射率呈逐步降低至相对稳定趋势。南极主要煤系地层的发育揭示晚古生代-早中生代时期,南极温暖湿润、植被繁茂,沉积环境与如今存在巨大差异,现存煤系地层多发育于河、湖相沉积交错处。煤系地层发育热演化史揭示,南极热变质煤系地层的形成与冈瓦纳大陆裂解有关,弗拉尔大火山岩省沿横贯南极山脉的线性分布特征与典型二叠纪煤系地层分布特征耦合,侏罗纪短期集中热事件形成的岩脉侵入可以作为煤系地层热蚀变开始的信号,白垩纪末的冈瓦纳大陆进一步裂解形成的热升温,可能是导致南极煤系地层呈现高煤阶、高成熟度的主因。

关键词:南极;二叠纪;煤系地层;岩相古地理;热演化史;冈瓦纳裂解
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Stratigraphic distribution of coal measures in Antarctica and its implications for breakup of the Gondwana

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Abstract: The coal measure resources in Antarctica possess great potential yet have received limited research. The discovered coal measures are predominantly Permian strata, with a few being Mesozoic-Cenozoic strata. The coal measures are essentially distributed in the Transantarctic Mountains and Prince Charles Mountains, with some parts found in West Antarctica. The coal-abundant strata in the Transantarctic Mountains are mainly Permian-Triassic

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Victoria Group of the Bacon Supergroup, and the coal-abundant strata in the Prince Charles Mountains are mainly Permian Bainmedart Coal Measures of the Amery Group. The coal in Antarctica exhibits the characteristics of a high thermal order and is mostly thermal metamorphic coal. The coal in the Transantarctic Mountains is mostly anthracite, super anthracite, or natural coke, which has the characteristics of high alteration. The coal in the Prince Charles Mountains region has the characteristics of high volatility and low sulfur. The vitrinite reflectance, which represents the maturity of coal measures, gradually decreases to a relatively stable trend as the formation age from old to new in the Bainmedart Coal Measures. The development of major coal measures in Antarctica reveals that during the Late Paleozoic and Early Mesozoic, the Antarctic was warm and humid with lush vegetation, and the sedimentary environment was vastly different from that of today. The existing coal measures were mostly developed at the intersection of river and lake sedimentary facies. The development and history of the thermal evolution of coal measure disclose that the formation of Antarctic thermal metamorphic coal measure is related to the breakup of Gondwana. The linear distribution along the Transantarctic Mountains of the Ferrar Large Igneous Province is coupled with the location of typical Permian coal measures, and the dike formed by the Jurassic short-term concentrated thermal event can be regarded as the signal of the commencement of thermal alteration of the coal measure, while the heat rise caused by the further breakup of Gondwana at the end of Cretaceous may be the main cause of the high coal rank and high maturity of the Antarctic coal measure.

Key words: Antarctica; Permian; coal measure; lithofacies paleogeography; thermal evolution history; Gondwana breakup

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南极几乎被冰雪完全覆盖，具有非常极端的自然环境，远离人类活动密集区使其保留了原始封闭特征，是目前地球上最少被勘测的大陆。科学家们通过对比南方诸大陆在冈瓦纳大陆时期的毗邻关系，推断南极大陆蕴含丰富的矿产资源，这一认识也逐步被各国极地考察与极地科学研究所证实。对铁矿资源与煤炭资源赋存的预测，也为南极博得了“铁山”和“煤山”的称号。依据少量地质露头观测结果，前人推断南极煤的储量可达约 5 000 亿吨（朱建钢等，2005）。但由于南极环境的极度恶劣，煤炭的开采和运输极其困难，综合考虑到信息缺乏、成本高昂、环境脆弱、实施困难和全球竞争等因素，南极的煤被认为是一种不经济的资源（Rose and Mcelroy, 1987）。此外由于南极洲受到国际保护协议的严格限制，目前尚未有任何大规模的煤炭勘探和开采计划。随着人类极区考察认知程度和科学技术水平的提升，在未来对南极资源开发利用将可能会成为全人类共同的选择（Temminghoff *et al.*, 2007）。

南极煤炭资源科学研究自 20 世纪下半叶开始持续至今（Merrill, 2016）。首次大陆煤炭资源的发现源自 20 世纪初英国南极探险队（Schopf and Long, 1966），后续科研工作者在南极大陆多地也都发现了煤层（Rose and Mcelroy, 1987）。自 1961 年《南极条约》生效以来，南极煤及矿产资源便受到条约的保护，任何形式的开采和勘探活动均不再被允许，这也导致了后续关于南极煤研究资料的短缺。20 世纪 50 年代后，随着极地系统科学研究的深入，南极洲的地质、气候和环境全面研究的开展，一定程度上再次推进了对南极洲煤炭资源的科学认知程度。

丰富的有机质是煤形成的必要条件，现如今南极“白色荒漠”的环境是不适宜孕育煤系地层的，南极煤资源的发现说明在地质历史时期内南极也曾绿草成茵、植被繁茂。大量南极二叠系煤系地层的存在，揭示了二叠纪的南极处在南半球高纬度地区，位于冈瓦纳古大陆的核心（McLoughlin, 2001）。煤系地层的分布特征及岩石地球化学特征，与古沉积环境及成岩过程息息相关。对南极煤系地层开展相关研究，不仅能够了解南极大陆煤资源状况，也有助于南极大陆古地理的恢复与重建，对推进地质历史时期内南极地质演化与气候变化认识具有重要意义。本研究通过搜集国际国内南极煤相关的研究报告与文献资料，对南极煤的分布特征及岩石地球化学特征进行归纳与分析，探讨煤系地层的构造沉积地质意义，以期获得对南极大陆构造演化、中-新生代南极构造沉积环境变化、冈瓦纳大陆裂解过程认识的相关启示。

1　南极大陆地质背景

从大地构造特征上看,南极大陆主要由东南极克拉通、西南极中-新生代活动带及两者之间的早古生代罗斯造山带(即横贯南极山脉)组成(图 1)。东南极具备前寒武大陆特征,地壳较厚,地体多被冰盖所覆盖,基岩出露主要在沿岸地区,发育有南极最古老的内皮尔杂岩(3 930±10 Ma)(Black *et al.*, 1986)。西南极主要是由中生代科迪勒兰带构成,地壳较薄,多为年轻地体组成,与环太平洋边缘的其他地区相当(Dalziel, 1983),基岩主要出露在玛丽伯德地、埃尔斯沃地和南极半岛区域。横贯南极山脉总长约 2 500 km,宽度约为 200 km,海拔超过 4 000 m,将东南极和西南极分开,其基底和盖层分别与东、西南极地块相关(陈廷愚等, 1995);构造特征上横贯南极山脉保存了从罗迪尼亚超大陆裂解到活动大陆边缘形成的长时地质记录;地理特征上其与澳大利亚德拉美造山带相连(Faure and Mensing, 2010);地层结构上横贯南极山脉由隆起的平坦地层断块组成,大部分范围由贝肯超群(泥盆纪至三叠纪)和中侏罗统费拉尔白云岩和科克帕特里克玄武岩组成(Faure and Mensing, 2010),还发育有晚元古代至奥陶纪褶皱沉积、变质沉积岩、花岗岩(Collinson *et al.*, 1994)。

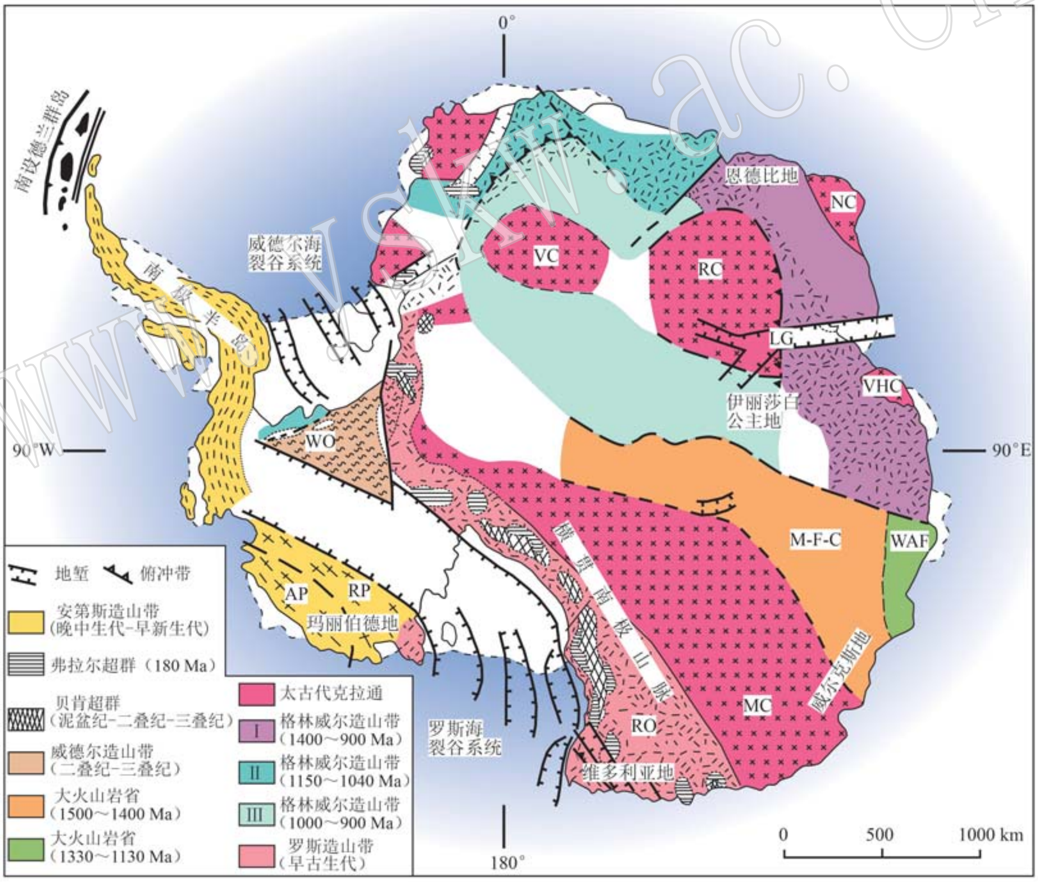

图 1　南极地质构造简图(据 Talarico *et al.*, 2022)

Fig. 1　Schematic geological map of Antarctica (modified after Talarico *et al.*, 2022)

AP—阿蒙森火山岩省; RC—鲁克克拉通; RP—罗斯火山岩省; VC—瓦尔基里克拉通; VHC—西弗尔丘陵克拉通; WAF—威尔克斯-奥尔巴尼-弗雷泽造山带; NC—纳皮尔克拉通; LG—兰伯特地堑; WO—威德尔造山带; RO—罗斯造山带; MC—莫森造山带; M-F-C—马都拉-佛利斯特-库帕那火山岩省

AP—Amundsen Province; RC—Ruker Craton; RP—Ross Province; VC—Valkyrie Craton; VHC—Vestfold Hills Craton; WAF—Wilkes-Albany-Frazer Orogen; NC—Napier Craton; LG—Lambert Grapen; WO—Weddell Orogen; RO—Ross Orogen; MC—Mawson Craton; M-F-C—Madura-Forrest-Coompana Province

白垩纪之前南极洲是冈瓦纳大陆的一部分，在早侏罗世期间（约 180 Ma）开始分裂，随后受到海道向内陆扩展的强烈影响，南极大陆逐步与周边陆块分离（Yaxley *et al.*, 2013）。印度板块在早白垩世与南极洲分离，并开始迅速向北移动；澳大利亚板块和南极洲之间在晚侏罗世时期已开始发育伸展和裂谷作用，最终在 95 Ma 之后才分离开来（Veevers and Eittreim, 1988）；南极半岛顶端和南美洲南部是冈瓦纳大陆最后一个主要连接点，直至新生代渐新世这一联系断裂使得南极洲孤立，导致了寒冷的南极绕极流形成（Barker and Burrell, 1977）。在整个白垩纪冈瓦纳分裂的同时，古太平洋板块沿着冈瓦纳的西南（太平洋）边缘持续向南极洲俯冲，影响了从南极半岛到玛丽伯德地到新西兰的整个边缘（Barker, 1982; Cooper *et al.*, 1982）。

冈瓦纳中生代末裂解的另一直接证据为弗拉尔大火山岩省（Ferrar Large Igneous Province），沿横贯南极山脉线性分布超 3 500 km，并向澳大利亚东南部延伸（Elliot and Fleming, 2008）。弗拉尔大火山岩省由侵入岩、火山碎屑岩和喷出岩等玄武质岩浆产物组成（Elliot and Fleming, 2008, 2018; Elliot *et al.*, 2021），地质年代结果限定为 183 Ma 左右，岩浆活动持续时间集中在 1～2 Ma 或者更短的时间间隔内（Elliot and Fleming, 2008; Burgess *et al.*, 2015），表现为板内裂解的短期强烈侵入与岩浆事件（Elliot *et al.*, 1999; Elliot and Fleming, 2021），对横贯南极山脉贝肯超群沉积产生明显的侵位影响（Bomfleur *et al.*, 2014）。

2　南极煤系地层分布及岩石地球化学特征

2.1　南极煤系地层分布特征

南极煤系地层分布区域特征明显，二叠系煤层主要分布在横贯南极山脉沿线和查尔斯王子山地区（图 2）。沿横贯南极山脉几乎均可见二叠纪-三叠纪煤系地层的出露（Crohn, 1959; Rose and Mcelroy, 1987）。

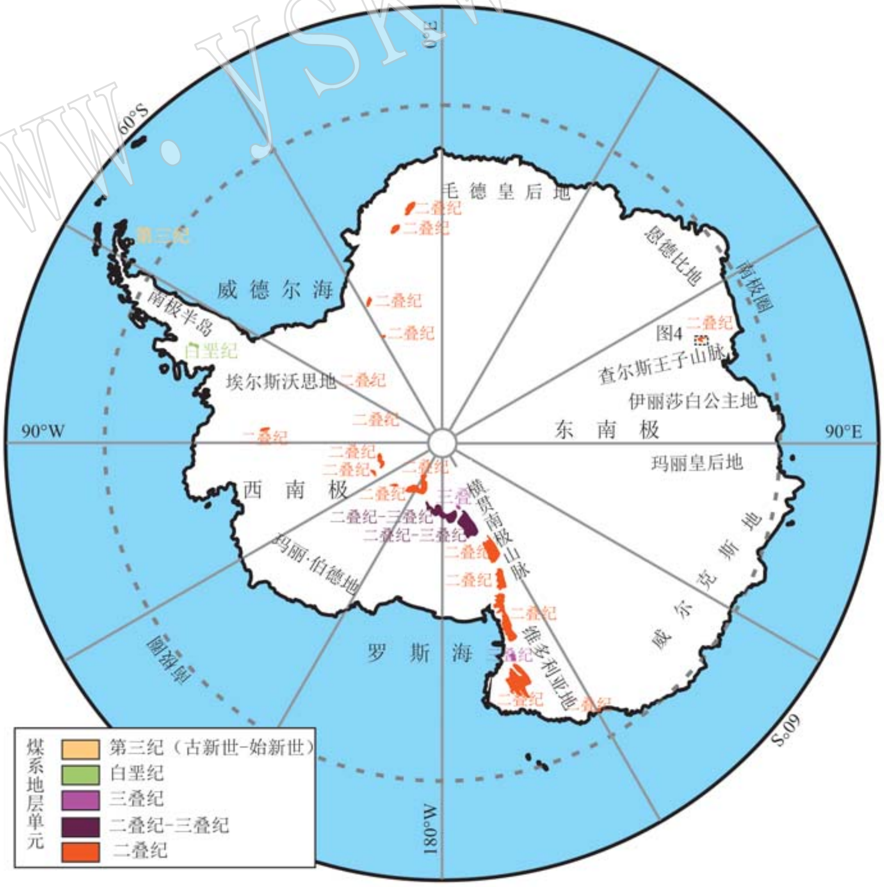

图 2　南极主要煤系地层分布示意图（据 Bradshaw, 2013; Merrill, 2016 修改）

Fig. 2　Map of coal measure in Antarctica (modified after Bradshaw, 2013; Merrill, 2016)

维多利亚地二叠系韦勒组煤系区内分布明显(Isbell and Cúneo, 1996)。毛德皇后地海姆弗伦特山脉、毛德皇后山脉均有二叠系维多利亚群毛德皇后组煤系地层的出露(Barrett, 1965; Bauer, 2009)。西南极埃尔斯沃思地和埃尔斯沃思山脉地区,存在晚二叠世极星组顶部煤层出露(Elliot *et al.*, 2016)。此外南极半岛区域也发育有部分中生代白垩纪煤与新生代第三纪煤,乔治王岛始新世-渐新世狮子湾组地层有薄层褐煤出露(Birkenmajer *et al.*, 1991)。

2.1.1 横贯南极山脉(TAM)的煤系地层

横贯南极山脉(TAM)横跨南极洲,从太平洋延伸到大西洋,是东南极洲和西南极洲的边界(Fitzgerald, 1994)。其形成过程目前尚未得到共识,普遍认为是横贯南极山脉的形成过程导致冈瓦纳大陆裂解及后续构造活动,也有认为横贯南极山脉是南极西部裂谷系的异常高缘(Behrendt and Cooper, 1991)。横贯南极山脉含有大量的二叠纪煤系地层基本上沿横贯南极山脉呈线状分布(图2)。自20世纪60年代起多个国家在横贯南极山脉开展数次科学考察,获取了包括南横贯南极山脉、中横贯南极山脉和南维多利亚地的众多煤样品,目前均保存于俄亥俄州立大学的极地岩石储存库(PRR)中。前人基于上述样品开展了一系列针对横贯南极山脉煤系地层的科学研究工作(Schopf and Long, 1966; Rose and Mcelroy, 1987; Coates *et al.*, 1990),并对横贯南极山脉煤的地质特征、质量和资源量做出了总结(Coates *et al.*, 1990)。

南极大多数已知的煤均位于横贯南极山脉断块的暴露地层中(Schapiro and Gray, 1966),富煤地层主要为贝肯超群(Beacon Supergroup)中的二叠纪-三叠纪维多利亚群地层。贝肯超群形成于弧后前陆盆地(Collinson *et al.*, 2006),横贯南极山脉的大部分区域由该地层组成(Barrett *et al.*, 1986; Faure and Mensing, 2010)。南极代表性二叠系含煤/富有机质沉积岩,如俄亥俄岭的格洛索普特里斯组(Gloopteris Formation)、尼尔森高原和威斯康星岭的毛德皇后组(Queen Maud Formation)和比德莫尔冰川区域的巴克利组(Buckley Formation),以及南维多利亚地韦勒煤系(Weller Formation)都是贝肯超群的一部分(图3)。

格洛索普特里斯组(Gloopteris Formation)被认为是发育于晚二叠世(270~250 Ma)的煤、砂岩、页岩的循环沉积(Long, 1965; Collinson *et al.*, 2006; Faure and Mensing, 2010)。格洛索普特里斯组单个煤层厚度为1.2~3.6 m,煤层总厚度约为23 m(Schopf, 1962; Schopf and Long, 1966; Faure and Mensing, 2010)。煤和碳质页岩层中发育有二叠纪舌蕨和羊齿蕨叶片化石(Schopf, 1962; Cridland, 1963; Long, 1965; Faure and Mensing, 2010)。巴克利组(Buckley Formation)包含了最广泛的煤系,发育范围可从伯德冰川延续至阿蒙森冰川(尼尔森高原)。巴克利组地层主要由砂岩、含碳质页岩、多植物化石煤层组成(Barret, 1969; Barrett *et al.*, 1986; Faure and Mensing, 2010)。煤层厚度一般为1~2 m,与格洛索普特里斯组相似,最厚的煤层可达约10.7 m,位于伊丽莎白女王山脉的皮乔托山区域(Barrett *et al.*, 1986)。韦勒煤系(Weller formation)位于维多利亚地南部,由炭质砂岩和粉砂岩组成,同样保存有二叠纪舌蕨和羊齿蕨叶片化石,表明地层时代上与格洛索普特里斯组大致对应(Long, 1965; Collinson *et al.*, 2006; Faure and Mensing, 2010)。横贯南极山脉南维多利亚地三叠纪拉什利组是维多利亚群的上部地层单元,发育时代为中-晚三叠世,地层厚度约为520 m,其中煤线与砂岩、粉砂岩、碳质页岩呈旋回层序特征(Tewari *et al.*, 2015)。

2.1.2 东南极查尔斯王子山脉(PCMs)的煤系地层

埃默里群贝恩梅达特煤系是东南极查尔斯王子山脉著名的二叠系煤系地层(图2),也是区域最主要的含煤地层,主要分布在查尔斯王子山脉环比弗湖(Beaver Lake)区域(图4a)。埃默里群由老至新包括拉多克砾岩(Radok Conglomerate)、贝恩梅达特煤系(Bainmedart Coal Measures)和弗拉格斯通岩滩组(Flagstone Bench Formation)3套地层单元,主要由长石砂岩和次石英砂岩组成,还包括砾岩、粉砂岩、泥岩、页岩和煤线等次要组分(图4b)。贝恩梅达特煤系与拉多克砾岩呈不整合接触,而与弗拉格斯通岩滩组呈整合接触(McLoughlin and Drinnan, 1997a, 1997b)。拉多克砾岩组见少量煤层,而弗拉格斯通岩滩组则完全不含煤层(图4b)。

贝恩梅达特煤系为浅灰色长石砂岩、粉砂岩、页岩与煤互层的二叠系地层单元(Fielding and Webb, 1995; McLoughlin *et al.*, 1997a, 1997b),由底至顶6个岩段依次是达特菲尔德斯(Dart Fields)砾岩段、特泊勒杰(Toploje)段、龙齿群(Dragons Teeth)段、格洛索普特里斯冲沟(Glossopteris Gully)段、格兰杰(Grainger)段和麦金农(McKinnon)段(McLoughlin and Drinnan,

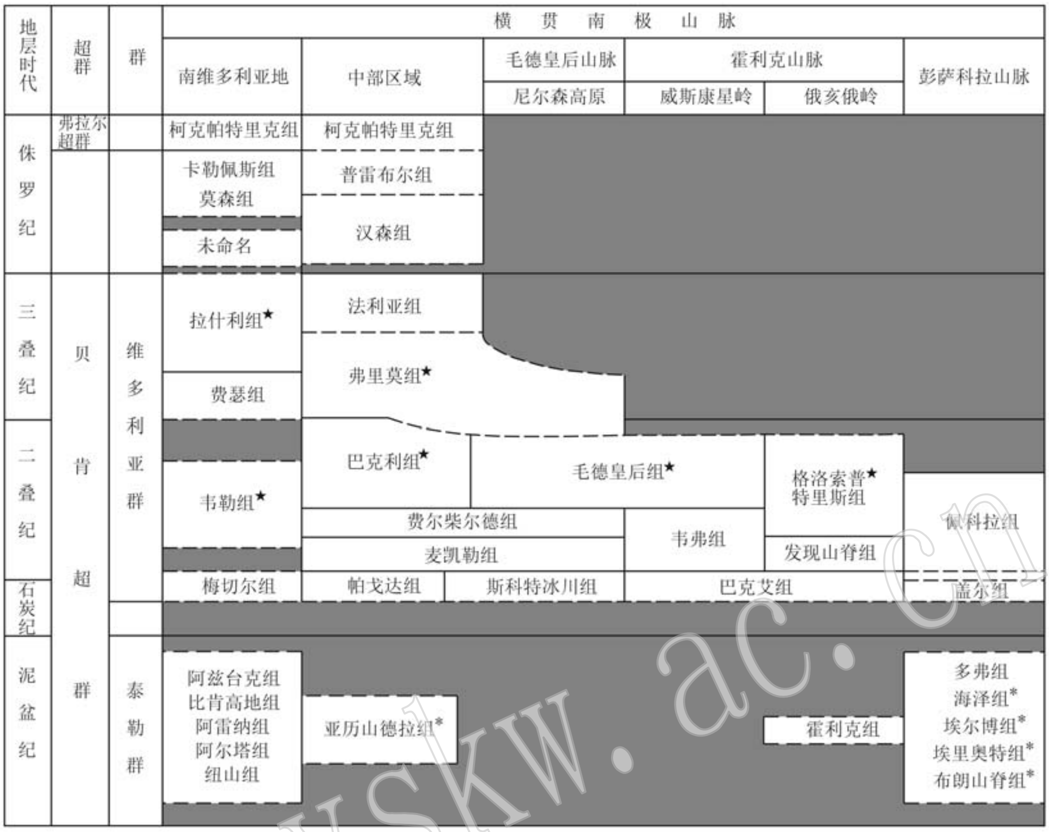

图 3　横贯南极山脉贝肯超群地层与煤系地层(据 Long, 1965; Collinson *et al.*, 1994; Elliot, 2013; Elliot *et al.*, 2017; Sanders *et al.*, 2023 修改)

Fig. 3　Beacon supergroup and coal measure of the TAM (modified after Long, 1965; Collinson *et al.*, 1994; Elliot, 2013; Elliot *et al.*, 2017; Sanders *et al.*, 2023)

带黑色五角星表示含煤地层,带星标表示地层年代不确定

black pentagram indicates coal measure, asterisk indicates stratigraphic age with uncertainty

1997a, 1997b),由向北或北东向流动的低弯度河流沉积与低能河泛盆地和泥沼沉积在时空上交替演变形成(Fielding and Webb, 1995; McLoughlin and Drinnan, 1997a, 1997b)。贝恩梅达特煤系含 100 多条煤层,煤层大多呈黑色,为碎屑或层状结构,总厚度达 80 m,单一煤层厚度大部分在 0.2~1.5 m 之间,一般平均厚度超过 0.7 m,煤层厚度较为稳定,连续性好可延伸数公里(Holdgate *et al.*, 2005)。

2.2　南极煤系地层的岩石地球化学特征

前人通过对南极煤系地层开展岩石学和地球化学研究(Schapiro and Gray, 1966; Schopf and Long, 1966; Coates *et al.*, 1990; Sanders and Rimmer, 2020),评估了煤参数特征(如镜质组反射率和挥发物)与成熟度之间的关系,推进了对南极煤的组成特征、赋存条件、热蚀变历史的了解(Pearson and Murchison, 1999; Rimmer *et al.*, 2009; Presswood *et al.*, 2016; Sanders and Rimmer, 2020)。南极已报道的煤多为受岩浆侵入作用影响的煤层,与正常埋藏成熟的煤相比,其成熟路径有所不同,不遵循正常成熟度升高、镜质组反射率升高、挥发性物质降低的(Rr-VM)趋势(Presswood *et al.*, 2016; Rahman *et al.*, 2017; Li *et al.*, 2018)。

2.2.1　横贯南极山脉(TAM)的热变质煤

南极的煤阶高于任何年龄相当的冈瓦纳煤,主要是由于南极煤系地层受侏罗纪辉绿岩岩脉和岩基广泛侵入的影响(Schopf and Long, 1966; Coates *et al.*, 1990; Sanders and Rimmer, 2020)。二叠纪煤系地层被广泛分布的辉绿岩脉侵位或白云岩层覆盖,引起煤系地层不同程度的热蚀变(Schapiro and Gray, 1966; Schopf and Long, 1966; Coates *et al.*, 1990; Sanders and Rimmer, 2020)。较高的热蚀变水平在横贯南极山脉的煤中表现尤为明显,以煤的高

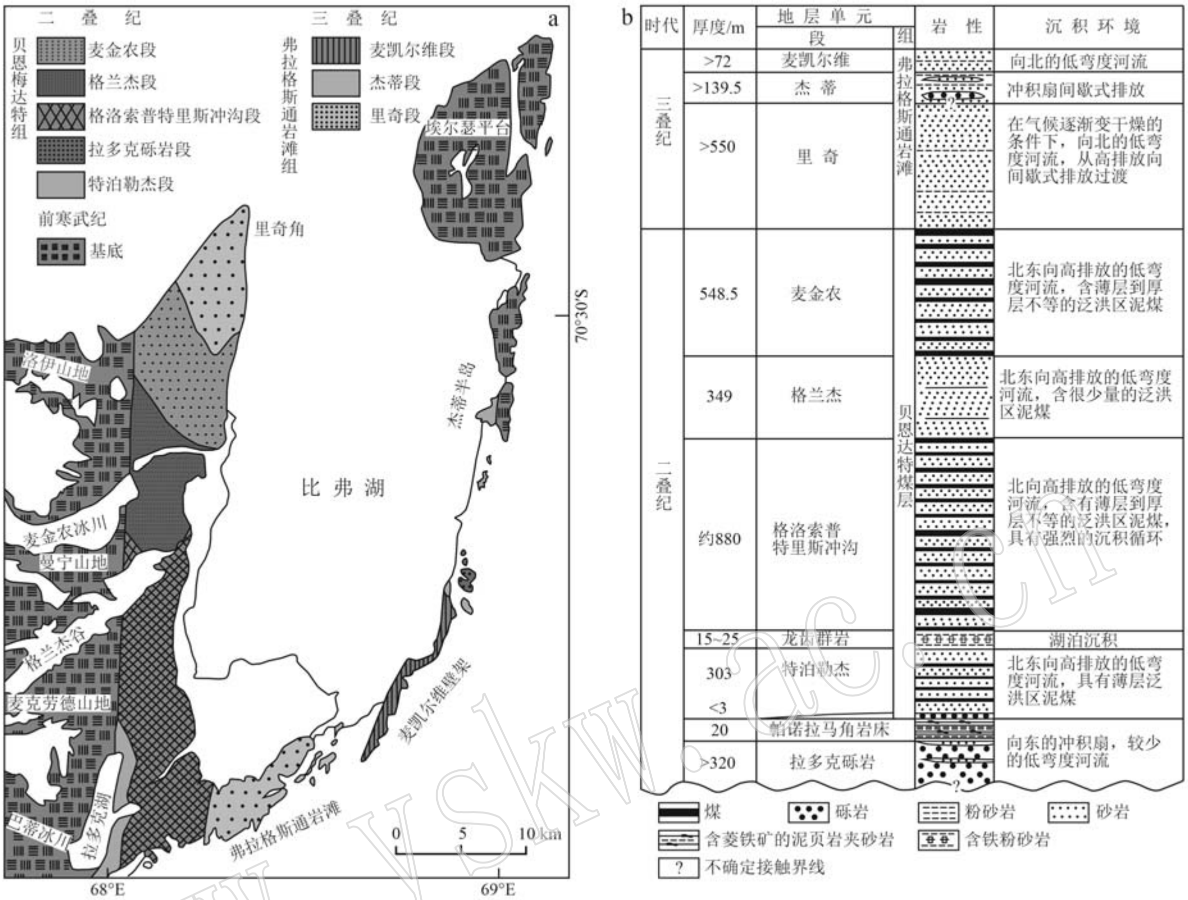

图 4　东南极查尔斯王子山比弗湖区域埃默里群煤系地层分布(a, 据 Fielding and Webb, 1995; Holdgate *et al.*, 2005 修改)和埃默里群地层和沉积环境(b, 据 Lindström and MeLoughlin, 2007 修改)

Fig. 4　Coal measure distribution in Amery Group, Beaver Lake area, PCMs (a, modified after Fielding and Webb, 1995; Holdgate *et al.*, 2005) and stratigraphy and sedimentary environment of Amery Group (b, modified after Lindström and MeLoughlin, 2007)

灰分为主要特征,煤样多为无烟煤或天然焦炭,有些样品特征甚至接近石墨(Schapiro and Gray, 1966; Schopf and Long, 1966; Sanders and Rimmer, 2020)。通过对过去在横贯南极山脉不同地点收集的 128 个二叠纪煤或富有机质页岩样本的镜质体反射率及有机碳分析数据统计后发现,横贯南极山脉煤和碳质页岩有机碳含量相当可观(3%~82%)(图 5a)。巴克利组样品有机碳含量表现为双峰特征,尽管许多巴克利组样本有机碳含量<40%,但并没有低至 1%~2%的样品(Sanders *et al.*, 2023)。大多样品具有非常高的镜质体反射率,表现出天然焦炭、无烟煤或偏无烟煤的镜质体反射率特征(图 5b)。

2.2.2　东南极查尔斯王子山脉(PCMs)的高挥发分煤

前人研究表明东南极查尔斯王子山地区的煤是具有中-高灰分含量、特低硫含量、高挥发分的烟煤(Crohn, 1959; Splettstoesser, 1980; Rose and Mcelroy, 1987; Holdgate *et al.*, 2005)。通过对比东南极查尔斯王子山埃默里群不同组段中煤系地层样品组构后发现,里奇、麦金农和格兰杰段样品镜质体反射率相似,格洛索普特里斯冲沟段、龙齿群岩段、特泊勒杰段到拉多克砾岩段样品平均镜质体反射率明显逐渐升高(图 6)(Holdgate *et al.*, 2005)。我国科学家在 2014~2015 年第 31 次南极科学考察期间,首次踏足北查尔斯王子山地区开展了地质科学考察并采集了珍贵的煤样品,这是我国科学家对南极煤系地层科学研究的首次有益尝试。通过对中国南极考察获取的煤样品进行煤岩学和煤化学分析,对比格洛索普特里斯冲沟段和麦金农段样品特征,发现煤层均以有机组分为主,且镜质组和惰性组占主要比例,硫化物只在麦金农段局部煤中发现,不同组段样品

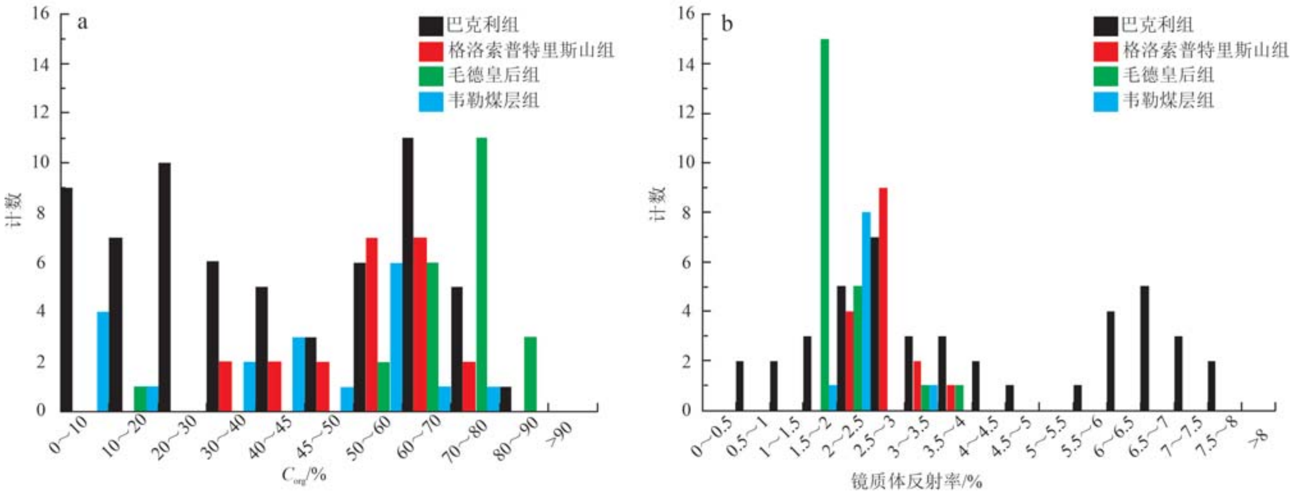

图 5　横贯南极山脉二叠纪煤系地层样品有机碳与镜质体反射率含量示意(据 Sanders *et al.*, 2023 修改)

Fig. 5　Organic carbon content and representation of vitrinite reflectance of Permian coal measure samples in the TAM (modified after Sanders *et al.*, 2023)

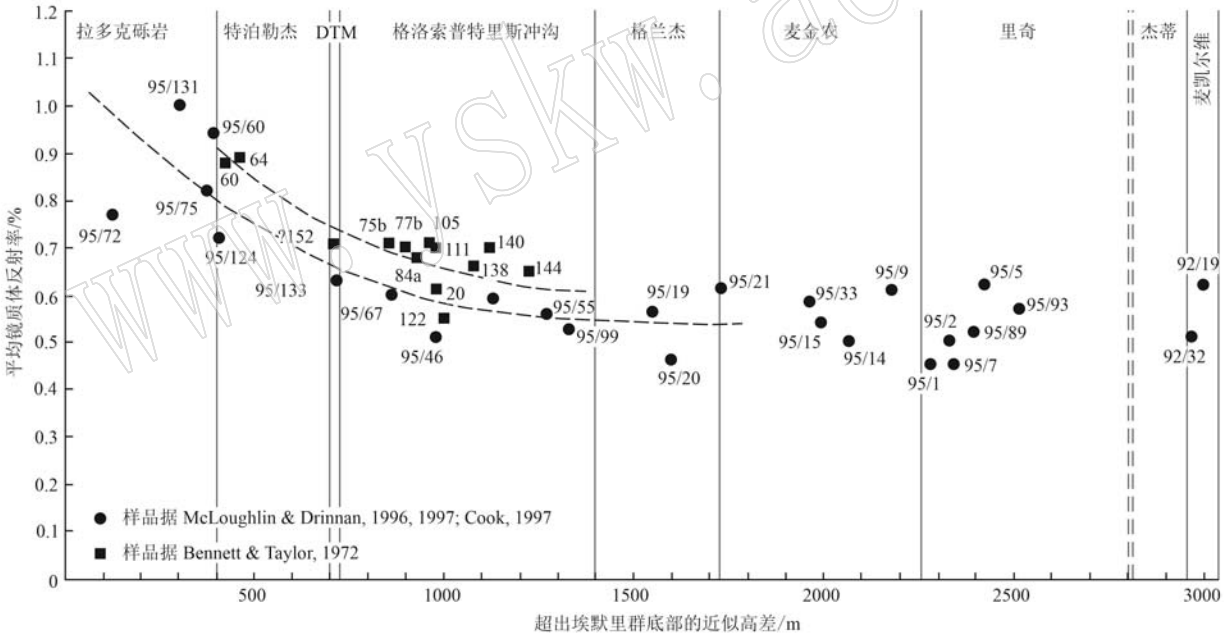

图 6　埃默里群不同组段煤/碳质页岩的镜质体反射率变化(据 Holdgate *et al.*, 2005 修改)

Fig. 6　Vitrinite reflectance values for coals and carbonaceous shale for the Amery Group (modified after Holdgate *et al.*, 2005)

化学组分方面也存在明显的磷、氟、氯含量差异(马立杰等, 2018)。

3　煤系地层地质意义分析

3.1　煤系地层形成与岩相古地理特征分析

南极最主要煤系地层产出于横贯南极山脉地区的晚二叠世韦勒组(Weller Formation)和晚三叠世拉什利组(Lashly Formation)地层,其中发现了丰富的与煤层相关的大、微植物化石(Chatterjee *et al.*, 2013; Awatar *et al.*, 2014; Tewari *et al.*, 2015)。韦勒组由砾岩、黑砂岩、页岩和煤组成,地层旋回产出,总厚度约 250 m,其中的含煤地层极易辨认(Chatterjee *et al.*, 2013)。韦勒组和拉什利组的厚煤层发育于湖沼相和曲流河相中,富含丰富的植物化石,而河道沉积中则明显缺乏厚煤层。对相应地层开展的沉

积学和岩石学研究发现了化石层微观木炭残留物，是大陆火山作用引起的古代森林火灾事件的证据(Retallack *et al.*, 2005; Kumar *et al.*, 2011, 2013)，表明二叠纪和三叠纪碳质物质的保存和煤的沉积可能与气候变化密切相关(Kumar *et al.*, 2013)。南维多利亚地的煤也是在河流相沉积中最为丰富，虽然在其他沉积环境中也有煤系地层赋存，但目前已报道的煤层丰富赋存均发育于湖相和辫状河与曲流河沉积交错区域。北维多利亚地二叠纪塔克鲁纳组与南维多利亚地二叠纪韦勒煤系似乎具有一定的相关性，地层学、区域相格局、古潮流取向和沉积史等方面的相似性，表明它们似乎沉积在相同或相似的沉积盆地(Isbell and Rubén, 1996)。

南极洲目前是世界上最干燥的“沙漠”之一，完全不适合植物生存，但在二叠纪和三叠纪期间，南极洲与印度、澳大利亚、南美洲和南非同是冈瓦纳大陆的一部分。晚石炭世-早二叠世冰盖的融化导致了气候的改善，气候逐渐炎热干燥，季节性降雨明显，导致冈瓦纳大陆舌苔植物群迅速进化，南极洲发育茂密的舌蕨和双蕨植物群(Pandita *et al.*, 2018)。在不同的冈瓦纳盆地，广泛的寒温带沼泽与繁荣的植物群落奠定了形成厚煤层的物质基础。煤的分布与岩相古地理特征相关，区域岩相古地理重建极有可能对区域煤系地层展布与赋存特征研究具有积极推动作用。

3.2 横贯南极山脉(TAM)煤系地层热演化史及其构造地质意义分析

前人通过对横贯南极山脉晚二叠世煤/碳质页岩开展岩石学和地球化学研究，评价了煤/碳质页岩的成熟程度和接触变质作用的影响，并对南极横贯南极山脉二叠纪煤的形成、掩埋及其热演化历史进行了重建(Sanders and Rimmer, 2020)。横贯南极山脉煤的累积和成熟历史可以划分为4个阶段(图7)：① 晚二叠世：影响煤系地层有机碳富集的因素主要有大气和生态因素、不同类型植物和植物器官(原显微物)的保存、野火(产生惰质岩)、沼泽内的退化；② 三叠纪-早侏罗世：煤系地层的埋藏成熟阶段，中等挥发性温度(~140~150℃)下发生成熟相关的组分变化，包括生物产甲烷、生烃和运移；③ 早-中侏罗世：受弗拉尔大火山岩省发育影响，横贯南极山脉的煤系地层发生接触变质作用，靠近岩脉和岩壁的煤，在较高温度(~500~600℃)发生焦化作用，挥发物大量损失，可能形成热解碳等显微结构变化，可能有热液蚀变；④ 中侏罗世至今：煤系地层持续的埋藏成熟(~200~210℃)，地层发生隆起、侵蚀、风化等地质作用，部分地区煤系地层暴露于地表。

横贯南极山脉煤总惰质含量较高，特别是活性半惰质含量较高，很少观察到壳质组，并且一些样品含有热解碳(Sanders *et al.*, 2023)。南极洲其他地区的煤所经历的热蚀变程度低于南极大陆架，毛德皇后地西部的阿梅朗高原组二叠系煤等级低至亚烟煤，镜质组反射率范围为0.4%~0.5%至3.3%(Bauer, 1997)；查尔斯王子山脉的贝恩达特煤系(二叠纪)的煤从亚烟煤到高挥发性烟煤不等，镜质组反射率0.50%~0.72%(Holdgate *et al.*, 2005)。东南极低阶煤与同为冈瓦纳煤的南非二叠纪煤观测结果较为一致，均受到岩浆侵入作用的影响(Bostick *et al.*, 1978; Snyman and Barclay, 1989)。横贯南极山脉煤的热历史独具特色，沉积堆积和岩浆侵入之间约有75万年的时间间隔，岩浆侵入作用发生时的煤层已具有中等挥发性沥青等级，表明与南非和南极洲其他地方的类似年龄的煤相比，横贯南极山脉煤的热流或埋藏深度要高得多(Sanders *et al.*, 2023)。横贯南极山脉的煤系地层被早侏罗世岩脉(183~177 Ma)侵入，这些岩脉与冈瓦纳大陆的分裂有关(Sanders and Rimmer, 2020)。也有人提出，在100 Ma左右整个横贯南极山脉有一段较晚的升温时期，热升温是源自冈瓦纳的进一步分裂(Molzahn *et al.*, 1999)。横贯南极山脉煤热历史表明，煤层沉积后期的热事件，确与区域大地构造演化的岩浆侵入及热升温相关。

4 结论

(1) 南极煤系地层成煤时代主要为二叠纪，分布区域主要为横贯南极山脉与查尔斯王子山地区。横贯南极山脉煤系地层沿山脉分布在南南极横贯山脉、中南极横贯山脉和南维多利亚地等地区，煤系地层主要发育于贝肯超群，煤系及碳质页岩产出在二叠系沉积岩格洛索普特里斯组、毛德皇后组、巴克利组以及韦勒煤系组；查尔斯王子山脉煤系地层主要分布在环比弗湖区域，煤系地层主要发育于埃默里群，其中贝恩梅达特煤层是区域最主要的含煤地层，拉多克砾岩组见少量煤层，而弗拉格斯通岩滩组则完全不含煤层。

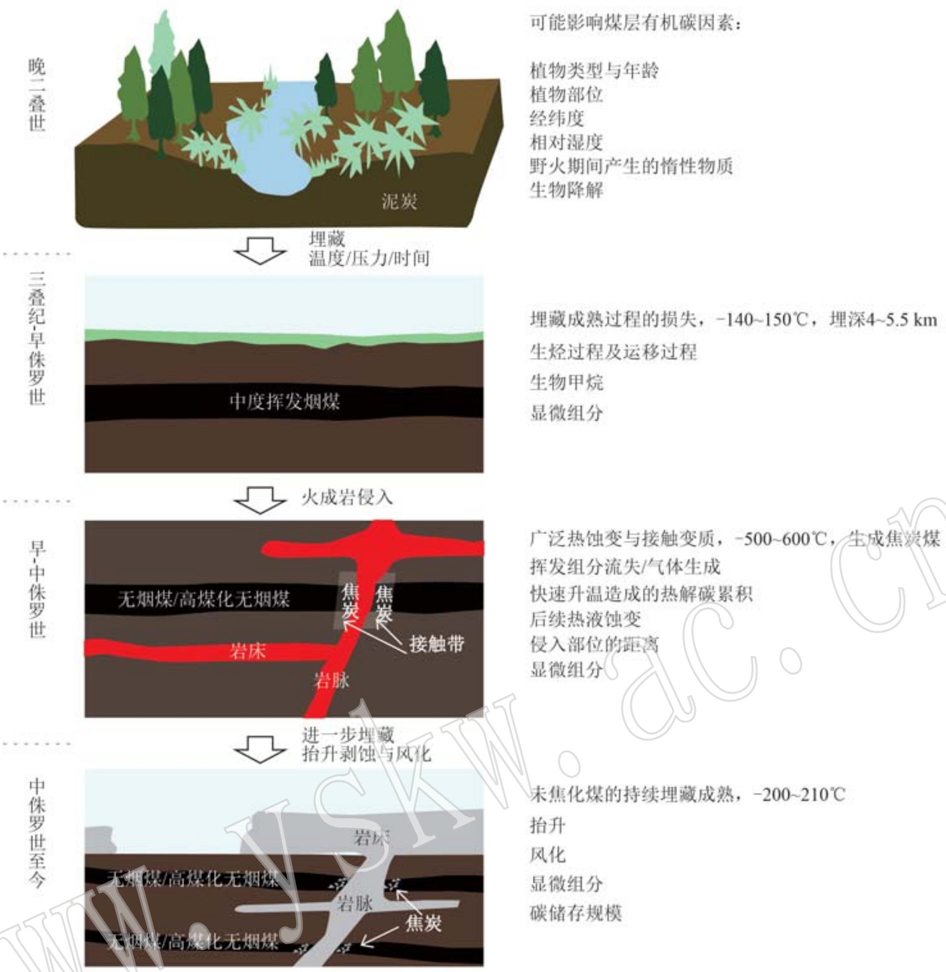

图 7　横贯南极山脉晚二叠世煤热演化史示意图(据 Sanders *et al.*, 2023 修改)

Fig. 7　Schematic diagram showing thermal evolution processes of Late Permian coal in Transantarctic Mountains (modified after Sanders *et al.*, 2023)

(2) 南极煤的岩石化学特征对鉴定煤阶,了解煤的赋存、组分及热蚀变历史具有现实意义。横贯南极山脉煤为热变质煤,多为无烟煤或天然焦炭,具有非常高的热蚀变特征；查尔斯王子山脉的煤为高挥发份煤,灰分含量相对较高,平均镜质体反射率相对较高,不同组段镜质体反射率按地质时代由老至新呈明显逐渐降低至稳定趋势。

(3) 不同区域煤的岩石地球化学特征,与沉积地层形成时的岩相古地理特征及后期构造运动改造直接相关。横贯南极山脉煤系地层主要发育于韦勒组和拉什利组的沼泽相和曲流相中。丰富的有机质及碎屑碳揭示晚古生代南极可能位于中-高纬度地区。煤的热演化史特征揭示,横贯南极山脉二叠纪煤与其他冈瓦纳煤具有明显差异,表现出高成熟度高热变质特征,变质煤发育热源与晚中生代冈瓦纳大陆进一步裂解及相应岩浆侵入作用有关。

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