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红层判识及其科学研究意义：从岩表特征模糊区分到地质基因定量判定

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摘 要： 红层是岩石圈层具有代表性的沉积地层之一．其分布之广，厚度之大，沉积之典型、地貌之完整，实属罕见．同时又是中华文明与文化传承的重要载体．长期以来，是地质、工程、生态与材料等领域关注的热点之一．但是，自1835年英国工程师和1925年李四光先生提出红层概念以来，至今尚未达成统一认识，缺乏较为系统的对红层判识及其科学意义的归纳总结，约束了对红层的全面认识，难以满足红层科学发展的需要．为此，较为系统地回顾了红层判识的岩表特征模糊区分、地貌颜色明确辨别、地层规律定性识别与地质基因定量判定等4个阶段的主要历程，归纳总结了不同阶段红层判识的科学意义，讨论了地质演化关联、对象范畴扩展与材料属性模型等红层判识趋势及其主要发展方向，在此基础上，提出红层判识的价值与展望．

关键词： 红层；地质基因；定量判识；范畴扩展；科学意义；沉积学；地层学．

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Review on Identification and Significance of Red Beds: From Rock Surface Feature Fuzzy Distinction to Geological Gene Quantitative Determination

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Abstract: The red bed is one of the representative sedimentary formations in the lithosphere. Its wide distribution, great thickness, typical deposition, and intact landforms are rare. At the same time, it is also an important carrier of Chinese civilization and cultural inheritance. For a long time, the red bed has been one of the hot topics in the fields of geology, engineering, ecology, and materials. However, since the concept of red bed was proposed by British engineers in 1835 and Mr. Li Siguang in 1925, there has not been a unified understanding of red bed, and there is a lack of systematic summarization of red bed identification and its scientific significance, which restricts a comprehensive understanding of the red bed and makes it difficult to meet the needs of red bed scientific development. Therefore, in this paper it systematically reviews the main process of red bed identification in four stages, including the vague distinction of lithological characteristics, clear identification of geomorphic colors, qualitative identification of stratigraphic patterns, and quantitative determination of geological genes,

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summarizing the scientific significance of red bed identification at different stages. It discusses the trends and main directions of red bed identification, such as geological evolution correlation, object category expansion, and material property models. Finally, based on this foundation, the value and prospects of red bed identification are proposed.

Key words: red bed; geological gene; quantitative identification; category extension; scientific significance; sedimentology; stratigraphy.

0 引言

红层是地球演化中最具有标志性的地层之一，是岩石圈表层分布最广、厚度最大的沉积地层之一，也是与人类生产生活、工程建造、资源开采等密切相关的标志性地层之一.其分布之广，厚度之大，沉积之典型、地貌之完整，实属世界罕见（Cloud，1972；Migoń，2020；周翠英等，2023）.目前已知的红层形成时间跨越了从前寒武纪、元古代、古生代，到中生代、新生代等不同地质时代（Williams，1969；Baker，1971；简文星等，2005；郭进京等，2014；Sillitoe and Rodríguez，2023），在七大洲和五大洋均有分布（Turner，1980；王成善和胡修棉，2005；Dorland，2006；吕璇和刘志飞，2017）.其中，我国红层主要是以中-新生代陆相沉积红色碎屑岩层及其风化物为主（彭华，2011；周翠英等，2023），亦有少部分古生代地层出露（Galtier and Broutin，2008）.我国是出露面积最大、地貌发育最丰富、唯一连续跨越六种气候带的国家（周翠英等，2023），主要分布西北、西南和东南等地区，厚度最大达近万米（居恢扬等，1983；郭福祥，1988；宋友桂等，2001；Tan *et al.*，2010；潘志新和彭华，2015）.同时，红层涵盖了从砾岩、砂岩到泥岩以及泥质粉砂岩和粉砂质泥岩等多种类型（周翠英等，2002；胡修棉等，2006；Jutras *et al.*，2011；He *et al.*，2023）.其性质特殊，主要体现在3个方面：(1)由于红层特殊的沉积环境、成岩环境和沉积历史，使得其孔隙比较发育，渗透率比较强，尤其是红色砾岩和砂岩，具有良好的孔隙度和发育良好的节理，通常具有较好的渗透性.因此，红层也是石油、天然气、矿石等资源、能源良好储层，对能源的利用与开发有着重要意义（Gutzmer *et al.*，2002；Schöner and Gaupp，2005；Meng *et al.*，2011；牛栓文和李继岩，2014）；(2)由于红层沉积时间跨度大、历时长，蕴含丰富的古环境与生命演化信息（Benison and Goldstein，2001；王红梅等，2001；Dorland，2006），因此也是地磁、构造等的重要研究对象（Klootwijk，1980；周萃英，2000；Grygar *et al.*，2003；焦养泉等，2008；Crowley *et al.*，2009）.因此，因其记录了气候、磁场、水文、地质等诸多行星演化信息受到学者广泛关注，长期成为学界研究热点和能源领域关注的焦点.(3)由于红层岩体结构中普遍存在粉砂质泥岩、泥质粉砂岩、泥岩等，富含高岭石、水云母和蒙脱石等黏土矿物，其强度低，遇水后软化和泥化作用强烈，因此，物理力学性质变幅大，遇水后极易迅速发生崩解软化等，导致滑坡、塌方、沉陷等地质灾害频发（赵明华等，2005；Zhang *et al.*，2014；刘俊新等，2015；穆文平等，2016；Miščević and Vlastelica，2019）.由此，红层是本底特征到底是什么？如何进行科学判识？就成为红层研究及其地质、工程、资源等领域共同关心的科学难题.这一难题经过近200年的研究得到不断完善.特别是近年来中、日、美、澳、加、法、德、英、意等国对红层相关研究加大投入（周翠英等，2023；Card and Montenari，2023；De Jaime-Soguero *et al.*，2023；Fakhraee *et al.*，2023；Forte and Kustatscher，2023；Jones *et al.*，2023；Uno *et al.*，2023；Rainoldi *et al.*，2024；Squire and Keays，2024），以期在红层地质、红层工程和红层生态与利用等方面取得突破.但是，目前缺少较为系统的红层判识及其科学研究意义的归纳总结，约束了对红层的全面认识，难以满足红层相关研究发展的需要.

为此，本研究通过系统梳理红层判识的研究过程，将红层判识研究划分为岩表特征模糊区分、地貌颜色明确辨别、地层规律定性识别到地质基因定量判定四个阶段；在此基础上，提出了不同阶段红层判识研究的科学意义，指出了红层判识研究的发展趋势，并对其未来主要发展方向进行了展望.

1 红层判识研究主要历程

国内外研究的分析表明，红层判识研究主要经历了从岩表特征模糊区分、地貌颜色明确辨别、地层规律定性识别到地质基因定量判定等4个阶段（如图1所示）.

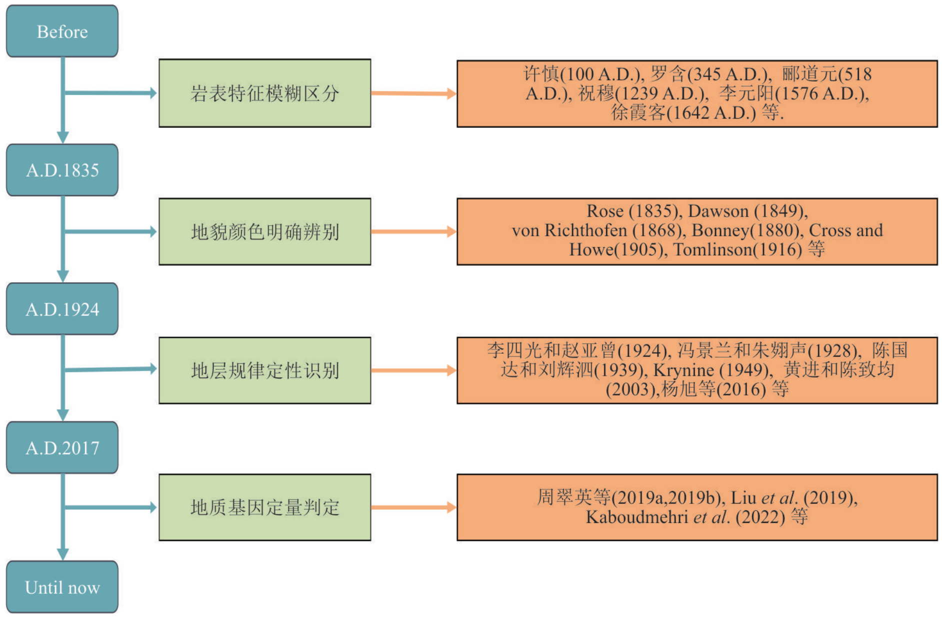

图 1　红层判识研究主要历程

Fig. 1　The main history of red bed identification research

岩表特征模糊区分阶段(1835 年之前):主要是指通过红层岩体局部特征与其他岩层对比分析进行无针对性区别,未形成明确学术概念,时间范围约为 1835 年之前.早在公元 100 年,中国汉代许慎将红层岩体描述为"丹巴越之赤石也".公元 345 年,中国晋代罗含提及的"湘水至清,虽深五六丈.其石子如蒲,五色鲜明,白沙如霜雪,赤岩若朝霞",是中国丹霞地貌命名的依据.公元 518 年,中国北魏郦道元对韶石进行了记录.韶石之所以在魏晋时就著名于世,主要是因为其独具特色的丹霞红岩地貌.公元 1239 年,中国宋代祝穆将麻姑山的地形地貌记载为"步入山门,榜曰丹霞,小有洞天,至忘归亭".公元 1576 年中国明代李元阳提及"红石岩,在城西北三里山,岩赤色如火".公元 1642 年中国明代徐霞客将红层岩表主要特征描述为"色如渥丹、灿若明霞".这类辨识方法可称之为岩表特征模糊区分方法.

地貌颜色明确辨别阶段(1835—1924 年):主要是指根据地层偏红色的主色调及相关沉积岩地貌特征进行判识,明确了红层这一提法,时间范围约 1835 年至 1924 年.在目前可考文献中,英国 Rose (1835) 在 West Norfolk 地质概况论述中第一次明确提出红层(Red beds),结合斯福克地质学大纲中的地图和剖面讨论它在剑桥戈尔特(Gault)当地具体的地貌、颜色及其成分(硫化物),但此时"红层 Red beds"尚未被定义.后来不少学者在此基础上进一步从地貌、颜色及其成分上进行了研究,例如:Dawson (1849) 提出部分红层的颜色似乎是由于铁过氧化影响下形成的,并研究了加拿大的 Nova Scotia 红层夹杂其他颜色地层的现象;von Richthofen (1868) 详细论述了中国南雄红层的地貌特点;Bonney (1880) 分析了 England 的 Brodick Bay 的红层地貌、岩性及其颜色,由此探讨红层可能的沉积环境;Ward (1894) 年通过总结美国 Black Hills 的红层地层颜色分布及地貌特点,以此描述红层互层特点.这些研究使人们对红层认识逐渐由地貌颜色深入到地质形成的特点,开始给出红层判识标准,即红层简单定义.例如:Richardson (1903) 通过对 USA 中 Black Hills 的红层微观特征与化学成分进行分析,探讨它们颜色的起源,试图对红层进行命名定义.Cross and Howe (1905) 通过对比其他主要由砂岩和砾岩组成的地层,提出红层是有深浅不同的偏红色调的岩层;Branson (1915) 对 Wind River Mountain 出露的连续红层的地质构造进行测量,并对其颜色、纹理、厚度产状进行了分析,以确定红层的来源.Tomlinson (1916) 致力于研究着色物质的成因和历史,最终认为红层是出露的偏红色调的碎屑沉积岩层.这一阶段关于红层地貌颜色研究不仅明确提出了红层,还使其判识由模糊到清晰,逐渐萌生并开始认识到红层色调、沉积相、岩性、沉积年代之间的关系,为基于地层规律定性的红层定性识别奠定了基础.上述辨识方法可称之为地貌颜色明确辨别方法.

地层规律定性识别阶段(1924－2017年):主要是指通过红层地层沉积相、形成年代与基本岩性等规律进行定性判识,形成了明确学术概念,时间范围约1924年至2017年.李四光和赵亚曾(1924)明确提出:红层主要是指中生代以来(即三叠系、侏罗系、白垩系和新生代古近系)的湖相、河流相、河湖交替相或是山麓洪积相等陆相碎屑岩,多以夹层和互层结构出现,从外表来看,其主要颜色为红色.这是从地层规律角度较早提出的红层判识方法,后来也长期作为红层基本概念使用.在此基础上,冯景兰和朱翙声(1928)将"丹霞层"引入红层的研究领域,根据岩石粒度粗细将南雄盆地红层划分为丹霞层和南雄层;Young *et al*.(1938)认为红层没有严格的定义,因为它可以在不同的地质年代沉积,并且颜色也不一定是绝对的红色;陈国达和刘辉泗(1939)提出"丹霞地形",推进了红层更广泛的认识;Krynine(1949)认为红层是在不同条件下产生的许多沉积类型的集合,它们唯一的共同特征是红色.进一步地,张忠胤(1958)提出:红层主要指侏罗系、白垩系、少量三叠系及早第三系形成的,已经成岩的,主色调为红色的泥岩、粉砂岩、砂岩等岩性的一套陆相及浅水湖相沉积物";van Houten (1973)认为红层是颗粒上、孔隙中或粘土基质中分散着红褐色氧化铁色素的碎屑沉积岩;曾昭璇和黄少敏(1980)认为:"红层是从中生代,特别是从侏罗纪到早第三纪的陆相红色岩系";Turner(1980)系统的总结了大陆红层,认为大陆红层由广泛的沉积相组成,包括洪积扇、河流冲积平原、沙漠、湖泊和三角洲的整个非海相沉积环境,它们不仅是红色的,而且经常含有各种不同比例的黄褐色岩层而显示出各种不同的颜色;黄进和陈致均(2003)认为丹霞地貌的物质建造为陆相红层(主要是红色砂岩、砾岩等碎屑岩类),并强调"红和陡".上述研究主要针对陆相沉积形成的红层,后来也有学者关注到海洋红层.王成善和胡修棉(2005)提出大洋红层的概念:"指海洋深水远洋、半远洋环境下,在富氧条件下形成的一套以红色-紫红色颜色为主的沉积物",这对红层判识和拓展范畴有重要推进作用;Pinti(2015)认为红层主要是由砂岩、砾岩、粉砂岩或页岩组成的沉积物或沉积岩,由于铁氧化物的存在,这些沉积物或沉积岩的颜色以红色为主.Zhou *et al*.(2016)针对中国红层赋存情况,提出红层主要指中新生代沉积的以红色为主的碎屑岩系及其风化物.这一阶段是红层研究由初步零星认识逐渐演变成活跃、发展的过程(盛莘夫等, 1962; 段嘉瑞等, 1978; Nance, 1988; 徐弘, 1995; Tan *et al*., 2010; Khorassani and Ghasemi-Nejad, 2015; Wang *et al*., 2016; Khankahdani, 2020),关于红层地层规律研究不仅揭示了其主要沉积地质年代、岩性、沉积相等判识依据,还将红层由陆相红层扩展到海陆相红层及其风化物,为基于地质基因的红层定量判定提供理论积累与实践基础.上述辨识研究逐渐形成了一套地层规律定性识别理论.

地质基因定量判定阶段(2017年－至今):主要是指通过红层相关大数据信息分析,发现红层演化的记录与控制载体信息,根据其中具有相似与突变并支持红层基本结构和性能的信息进行定量判识,这是一种类似生命基因的方法,可称为红层地质基因判识方法,时间范围约为2017年至今.周翠英等(2019a)根据EarthChem、GEOROC等红层数据,对比分析了全球陆海相晚泥盆纪、早石炭纪等不同时代红层与其他岩系在元素、氧化物、矿物等方面的异同,揭示了红层元素组合控制矿物、矿物组成控制宏观性质的规律,建立了红层元素、氧化物、矿物与单元结构之间的关联,提出了具有对红层演化有记录与控制载体信息作用的地质基因特征:FeO_T相对含量为4%～11%,且一般条件下,$Fe_2O_3/FeO>1$;K_2O+Na_2O相对含量为3%～6%,且一般条件下$K_2O/Na_2O>1$;$SiO_2+Al_2O_3$相对含量为55%～85%;造岩的黏土矿物与其他矿物比值为1:1～4:1;赤铁矿含量为3%～8%(孔令华, 2019; 周翠英等, 2019a, 2019b; Cui *et al*., 2024).这一判据不仅明确了红层定量判识的标准,还突破了海陆相、岩性限制对红层认识的约束与争论.Liu *et al*.(2019)对全球地球化学、矿物学和矿石地质记录进行新的汇编,其中将碎屑岩系等微量元素、矿物成分、沉积过程进行相同与不相同差异分析,尝试推测其地质成因.在此基础上,Liu *et al*.(2019)通过红砂岩在层流和湍流两种典型流态下的饱和试验结合数值模拟,弥补了动态水条件下岩石软化定量分析指标.Kaboudmehri *et al*.(2022)根据构造背景、沉积环境、主岩、植物化石的存在、几何形状、矿石结构、矿物学和蚀变行为对Toryan地区的产状归类为红层沉积.Yang(2022)通过岩心描述、粒度分析、薄片鉴定、扫描电镜观察、孔隙度和渗透率测试等方法,综合了钻井岩心、测井和地震资料,定量分析了红层成

岩作用过程对砂岩储层特征的影响，填补了研究区成岩作用定量研究的空白．这一阶段实现了红层定量判识，为红层深刻认识与新发现提供了理论依据与重要基础．以上以地质基因为基础的辨识研究就构成了红层的地质基因定量判定方法．

2　红层判识的科学研究意义

随着红层判识理论和方法的不断发展，根据不同红层概念，红层科学研究在红层地质、红层工程、红层生态、红层利用等方面产生了不同内涵与实际应用，对人类文明、生产、生活与发展具有重要意义．

岩表特征模糊区分方法，是人们初期利用局部特征辨识红层的方法，认识上尚存在较大局限，通过岩表特征区分和基本力学性质认识，主要开展红层的简单利用与地理描述等方面的实际应用．在简单利用方面，距今 3 800～3 500 年的中国洛阳二里头遗址发现采用加工后的红层砂岩作为柱下基础；中国闽越王城遗址、南越王墓、敦煌莫高窟、麦积山石窟、乐山大佛、丹霞山摩崖石刻及澳大利亚艾尔斯岩石、美国科罗拉多大峡谷、秘鲁彩虹山、希腊锡拉岛红色悬崖的遗迹遗址等多采用红层岩体作为基材．这些红层中的文物古迹和自然景观利用，使得红层成为了厚重的文化与文明承载体．在地理描述方面，《说文解字》、《湘中记》、《水经注》、《方舆胜览》、《万历云南通志》、《徐霞客游记》、《杂曲歌辞·行路难三首》、《飞来峰》等多处以红层特征为素材进行论述与表达情感．这些研究及其实践逐渐地推进了红层认识水平，但未能揭示红层形成、演化的深层规律与丰富材料性能．

基于地貌颜色明确辨别方法，使得人们逐渐认识到红层的特殊性，通过对红层地貌、颜色特征与形成演化规律的分析，主要开展红层地貌及少量工程地基研究等方面实际应用．在地貌研究方面，通过对红层区域范围内的纹理、沉积结构、褶皱、岩性、断裂发育程度等信息进行简单总结，开始关注红层与下伏地层间地质特征，尤其是对受岩性、区域地质构造、流水作用、物质基础等地球内力和地表外力的长期作用下的红层高原、红层山地和红层丘陵等多种地貌类型、地貌发育特征、颜色特征和地区差异进行对比研究（Walcott，1896；Condra，1907；Gulliver，1909；Lee，1918；Moses and Griffith，1925）．在工程地基研究方面，基于上述部分地区独特的红层地貌发育、岩性特征，总结降雨冲刷、地下水渗透蚀刻、地震等对工程地基基本性质的影响规律，开展适应于当地环境的相应简单的地基改良、加固与油井挖掘可能性及其支护等工程措施（Cope，1877；Hill，1892；Schwennesen and Meinzer，1914；Case，1915；Chadwick，1918；Irwin，1922）．这些研究及其实践直接推动红层相关科学理论与技术的形成，但依然是局部的且不够深入的．

基于地层规律定性识别理论，使得人们不断提升了红层形成、演化与特性的认识水平，通过定性揭示红层地质共性规律，主要开展红层地质、工程、生态与利用等方面的实际应用．在红层地质方面，专家们重点通过现场勘测、阐明红层灾变的地形地貌、地层岩性、地质构造、气象水文等条件，以及与地震、工程等的联系．在此基础上，概化红层地质体赋存条件，开展滑带体环剪试验、全应力应变渗透试验、耐崩解试验等，揭示红层岩土体静动态时的剪切、位移过程、应力-应变变化、渗透性演化及强度软化等规律，探讨红层崩塌、滑坡、泥石流发生机制．结合有限元、有限差分等数值模拟方法，研究地质作用对红层崩塌、滑坡、泥石流形成的影响规律（Mader，1985；杨宗才等，2006；Moufti and Mesaed，2015；张群等，2015；Wang *et al.*，2016；Yan *et al.*，2016；Yan and Kasanin-Grubin，2019）．在红层工程方面，学者们主要针对红层工程长期以来关注的主要地质问题，如复杂条件下红层软化、硬岩崩解、岩层蠕变效应、裂隙渗流等易导致大变形、塌方、岩爆、涌水突泥等病害，重点研究影响复杂条件下红层地质稳定性的共性规律（冯忠居等，2005；韩丽芳等，2009；Liu *et al.*，2012；Zhang *et al.*，2016a，2016b）．在红层生态方面，研究人员通过引入丰富的绿色新型功能材料用于生态修复，并通过大量室内、现场试验，对影响红层特性的规律进行研究，研发了相关配套技术，实现比传统技术更低碳、更环保、更节约的红层生态地质修复（何京丽等，2007；邵蕊等，2011；时卉等，2013；罗谷松等，2016；De Jaime-Soguero *et al.*，2023）．在红层利用方面，学者们主要集中在红层矿物材料复配与改性方面，引入高性能绿色材料等改性以不同级配颗粒为主的红层岩土体技术，揭示不同红层岩土体技术对红层地层的影响规律，以解决红层岩土材料性能提高及大规模应用技术的难题（Bensing *et al.*，2005；魏永幸，2009；Horiuchi *et* *al*., 2012; Nakano *and* Sakai, 2016).这些研究及其实践不仅极大地提高了红层科研究综合水平,也较为充分地发挥了红层服务人类的价值,但是仍难以满足红层灾害治理、工程安全保障、生态修复、功能材料利用和行星探索等方面不断提高的要求.

基于地质基因定量判定方法,使得人们第一次较为全面认识了红层组构及其形成演化规律,通过建立红层元素、氧化物、矿物与宏观性质之间的关联,主要在红层地质、工程、生态与利用等方面的实际应用取得了新的突破.在红层地质方面,专家们以基础地质为切入点,通过详实的地质调查分析、工程地质测绘、钻孔勘探、无人机、地统计学、GIS、近红外仪等手段,重点从矿物成分、微观结构、物理力学特性和水理特性等方面,对红层的地质特性、地形地貌条件、物质结构条件、地层岩性条件、沉积物成因等进行定量研究(Azizi *et al*., 2018; 闫琦玮等, 2020; Bábek *et al*., 2021; Meng *et al*., 2022; 李洪梁等, 2022).在红层工程方面,学者们主要通过数学力学分析、原位测试、物探试验、现场观测与室内试验等手段,对红层的矿物鉴定、物理力学性质及化学性质结果进行分析.结合排水为主、抗滑支挡为辅的工程措施,达到改善红层的易膨胀、崩解、泥化和软化特性的目的(Wang *et al*., 2017; Liu *et al*., 2018; Zhan *et al*., 2020; Xia *et al*., 2021; 李清波等, 2021; Sun *et al*., 2021; Yu *et al*., 2022; 许强和唐然, 2023).在红层生态方面,研究人员主要根据不同红层地貌破坏及荒漠化的程度,通过对红层特性-地表侵蚀-地貌发育-生态演化等外动力系统集成机制研究与试验分析,重点关注红层与地貌发育-自然灾害-水土流失-生态退化-综合地理环境-生产和生活之间相互关系,采用高性能酯类材料、生物酶纤维、聚合物固化剂水泥浆等材料(周翠英等, 2018; Lavrov, 2018; Bian *et al*., 2019; Xiao *et al*., 2022; Tan *et al*., 2023),开展红砂岭等红层地区的水土保持与生态治理(Li and Zhao, 1924; Higgitt and Rowan, 1996; Zhang *et al*., 2016a, 2016b; Yan *et al*., 2019; Yao *et al*., 2019; Zhou *et al*., 2021; Li *et al*., 2022);或者利用红层岩土体研制红层复合高分子材料(Huang *et al*., 2020, 2021; Zhou *et al*., 2020; Lai *et al*., 2022; Liao *et al*., 2022),开展边坡、戈壁、盐碱地、沙漠等生态修复.在红层利用方面,主要利用经过破碎、压实等处置后的红层岩土体,充分利用红层岩土体自身的特性,将其作为基本材料,开展成膜、改性、油气勘探、新材料研制等应用,并形成了适于不同地区配套技术,以推动管大范围内的适应性材料推广与应用(Li *et al*., 2018; Zhang and Liu 2018; 周翠英等, 2019a, 2019b; Zhou *et al*., 2020; 钟志彬等, 2020; Aygar and Gokceoglu, 2021);在行星探索方面,周翠英等(2023)采用红层地质基因定量判定方法,认为火星盖尔陨石坑下部地层与地球红层类似,并由此推论得到的火星古气候、古环境与地质演化等与前人研究结果一致;Wang *et al*.(2018)通过整合无人机和卫星拍摄的高分辨率图像,以及过去4年的实地调查,得出我国青藏高原柴达木盆地雅丹地貌的红层与火星上Medusae Fossae Formation(MFF)和Gale Crater处的沉积岩在颜色、地貌特征、侵蚀特征和成岩过程方面存在相似性;Benison(2006)通过对火星地层中的层理、交错层理、波纹痕、泥裂缝、位移蒸发岩结晶模具和赤铁矿结核等进行分析得出美国堪萨斯州中南部的中二叠世Nippewalla组红层与火星上子午平原伯的恩斯组在沉积构造和成岩特征等方面具有相似性.这些研究及其实践不仅统一了红层地质体特性的相关认识,还正在破解红层在不同赋存环境中演化的跨尺度难题,对红层灾害治理、工程安全保障、生态修复、功能材料利用及行星探索提供了有力支持,也为红层相关科学理论的进一步发展奠定了基础.

3 红层判识研究的发展趋势

地质基因定量判定理论已使得红层本身判识逐渐完善,但随着资源开采、工程建设、功能材料开发、行星探索等在广度和深度上的发展,以红层地质基因为核心的认识需要不断拓展,形成以红层本身为中心的不同岩层网络式知识体系,可在将来更好地服务人类(图2):主要有红层判识的地质演化、对象范畴与材料属性等3个主要方面.

红层判识的地质演化关联,主要针对侏罗纪、白垩纪、古近纪、新近纪、第四纪等不同地质时代红层形成演化的猜想(Simms and Ruffell, 1990; Morton and Hallsworth, 1999; 段其发等, 2012; 胡哲等, 2022),例如不同地质时代红层与形成时期的气候、水力条件具体关系是什么?这些关系对不同地质时代红层在地质基因的共性上存在何种联系?地质演化关联问题不仅涉及红层演变追溯性相关探索,也

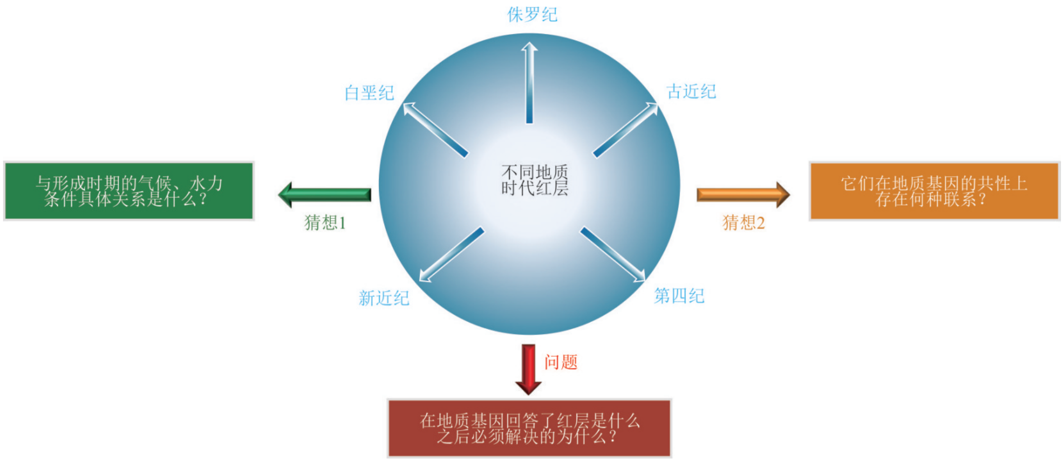

图 2　红层的地质演化对比

Fig.2　The geological evolutionary correlation of red beds

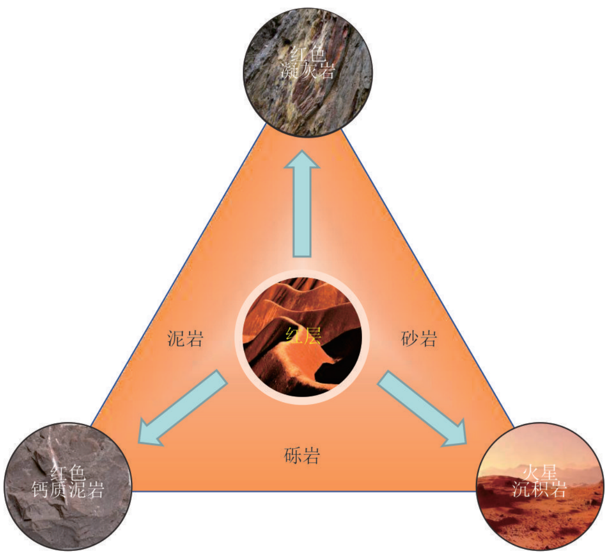

图 3　红层判识的对象范畴扩展

Fig. 3　Expansion of red bed identification

是在地质基因回答了红层是什么问题之后必须解决的为什么的问题，这对红层判识及其相关理论与技术发展具有重要意义．因此，红层判识的地质演化关联将推动红层相关猜想验证及相关行星探索．

红层判识的对象范畴扩展，主要针对在形成、组构、性质等方面与红层类似的岩层，例如红色凝灰岩、红色钙质泥岩、火星红层沉积岩等（Emeleus *et al.*, 1996；Stein *et al.*, 2018；李明和林宝玉，2022），如图 3 所示．这些岩层地质推演、工程建造、材料研发等方面时常遇到与红层类似的难题．通过对红层地质基因的判识方法拓展，形成类红层或广义红层的判识体系，将有助于发现不同岩层之间的内在联系，也可促进科研与实践难题的解决．因此，红层判识的对象范畴扩展将推动红层地质、工程、生态与利用的更广泛发展．

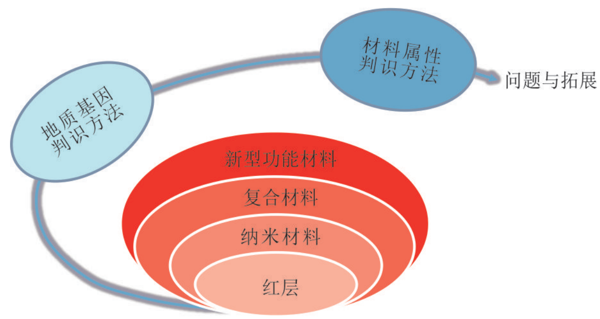

图 4　红层判识的材料特性模型

Fig. 4　The material property model for red bed identification

红层判识的材料属性，主要针对目前正迅速发展的红层利用问题，例如以红层为核心或基材的纳米材料、复合材料、新型功能材料等研发与应用（周永强等，2018；徐鹏等，2019；Huo and Sun, 2021）．这些问题揭示了红层判识方法中应存在一个与地质基因判识相对应的材料属性判识方法，如图 4 所示．红层作为一种天然的地质材料，其材料属性模型不仅可以从新的角度提出判识方法，也可以揭示红层更为本质的系统性特征，这将对红层的全面认识是有极大帮助的．因此，红层判识的材料属性模型将推动红层利用进入新的发展阶段．

4　结论与展望

红层判识理论和方法经过从岩表特征模糊区分、地貌颜色明确辨别、地层规律定性识别到地质基因定量判定的 4 个阶段发展，正不断完善，这一历程促进了红层地质、红层工

程、红层生态、红层利用的研究，对红层相关理论与技术发展有不可替代的价值．我们认为以下3个方面值得深入开展相关工作：

（1）红层地质基因定量判定理论将随着相关数据资源的不断丰富，形成具有更多细节的元素、氧化物、矿物与宏观性质之间关联，将在核心判识内容上不断细化，可在不同地质时代、岩层类型、赋存环境等方面进行精细判识，这对红层定量判识理论的完善十分重要．

（2）红层判识的地质演化关联、对象范畴扩展与材料属性模型等理论的深入研究，不仅将提升红层相关资源开采、工程建设、功能材料开发、行星探索等综合水平，也会促进其他岩层的相关研究．

（3）红层判识及其相关研究目前中国处于前沿领先地位，而红层本身作为全球甚至固体行星的一个标志性地层之一，中国应在适宜的时机协调相关国际研究机构，构建全球性红层研究计划，打破相关制约，以促进红层相关研究取得更大的进步．

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