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土耳其岩溶地质概况

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摘　要: 土耳其岩溶分布面积约占其国土面积的 40%, 发育典型的地中海气候类型岩溶, 根据构造特征, 从北向南分为四个不同的岩溶区, 其中托罗斯山脉是土耳其乃至地中海地区最大、最为发育的岩溶区, 具有很高的研究价值。文章在系统收集地质、构造及水文地质等资料基础上, 编制 1∶100 万土耳其岩溶地质图, 分析了影响岩溶发育的因素, 总结了土耳其岩溶分布规律、主要岩溶现象及资源开发利用现状, 为"全球岩溶地质"数据库建设和服务全球岩溶大科学计划提供支撑。

关键词: 土耳其; 岩溶地质; 岩溶分布; 洞穴; 岩溶泉

创新点: 系统地总结了土耳其岩溶分区特征、岩溶发育的影响因素及资源开发利用现状, 为全球不同类型岩溶地质对比提供了可靠资料, 为不同岩溶地区资源可持续利用、岩溶环境治理与保护提供可借鉴的实例。

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0　引　言

土耳其 783 562 km^2 的总面积中, 约有 40% 由石灰岩、白云岩和石膏等可溶岩组成[1-2]。土耳其的岩溶研究起步较晚, 早期主要是为国内洞穴探险者于 20 世纪 60 年代进行的洞穴研究, 土耳其最初只有两个洞穴研究组织: 由 Aygen 博士 1964 年建立的洞穴研究协会以及 Boğaziçi 大学 1973 年成立的洞穴学会。直到 20 世纪 80 年代, 国外洞穴探险者在托罗斯山脉发现了数量众多、发育规模庞大的洞穴, 在此之后土耳其的洞穴研究进入到飞速发展阶段, 研究人员在过去的 40 多年对大约 3 000 个洞穴进行了研究[1]。洞穴研究的飞速发展也使得科学家们开始从水文地质学[3-15]、地貌学[16-22]、洞穴生物学[23-30]、地球物理和地球化学[31-43] 等领域来研究岩溶的发育与演化及其环境效应。尽管如此, 大多数学者只是针对某一特殊区域内岩溶相关问题的研究, 很少从土耳其全国尺度系统分析并总结岩溶地质特征, 本文通过整合地形图、遥感影像图、地质图以及国外调查报告及文献资料, 编制完成 1∶100 万土耳其岩溶地质图, 从区域地质角度, 总结了土耳其岩溶地质特征、岩溶分布特征、岩溶发育的影响因素、主要岩溶现象及资源开发利用现状, 以期服务全球岩溶大科学计划和"一带一路"倡议。

1　地理、地质背景

1.1　地理环境

土耳其横跨欧、亚两大洲, 为爱琴海、黑海及地中海所环绕[44], 境内东高西低, 主要为高原和山地,

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沿海为狭长平原。亚洲部分主体为安纳托利亚高原，海拔为 800~1 200 m，高原北边为屈雷山脉，海拔为 2 000~2 500 m，西部山间多断陷盆地，南边为托罗斯山脉，海拔高达 3 500 m，沿地中海沿岸从西南向东北延伸（图 1），西南沿海地区为典型的地中海气候，冬季温和多雨，夏季干燥温暖[45]。土耳其年均降水量约为 643 mm，大多数水资源都蕴藏在东南部和黑海地区，可分为 26 个流域，最主要的河流是幼发拉底河和底格里斯河[46]。

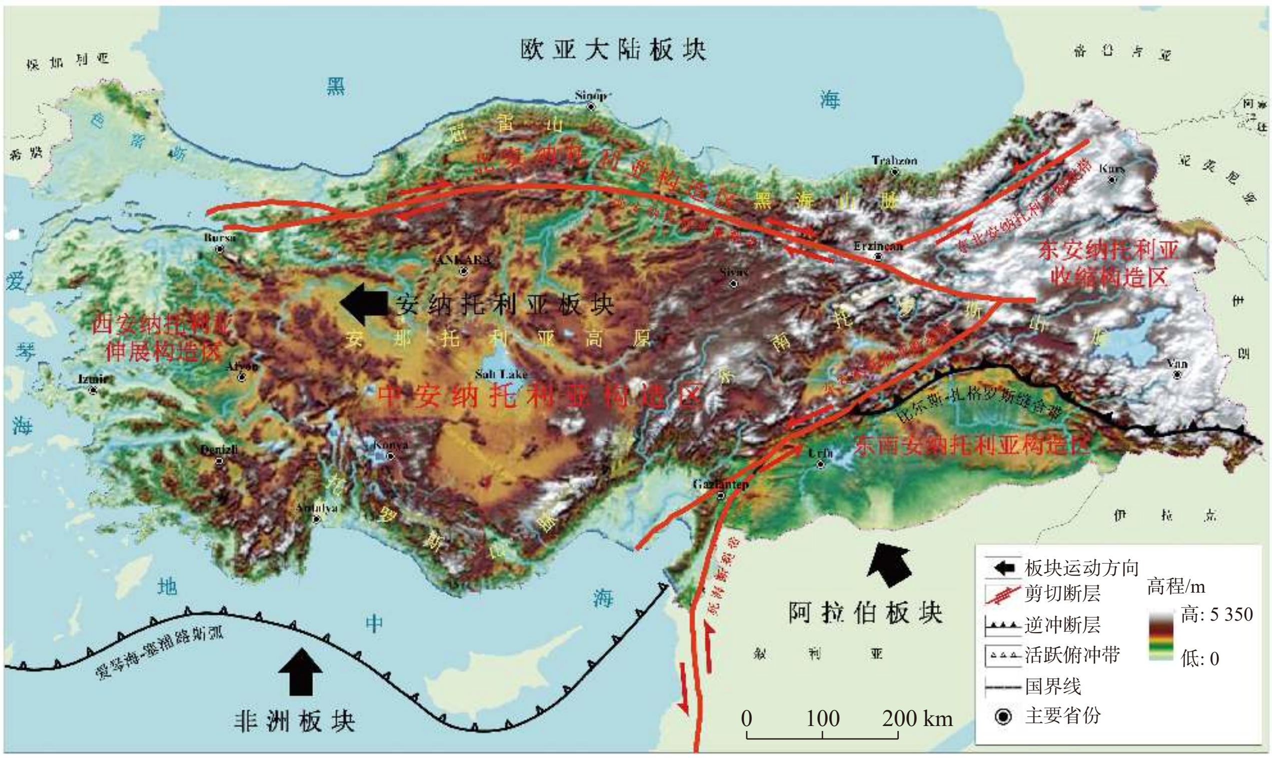

图 1　土耳其地理及构造简图（修改自 Erdin Bozkurt[47] 和 Raja[48]）

Fig. 1　Geography and structure map of Turkey (Modified from Erdin Bozkurt[47] 和 Raja[48])

1.2　地质背景

土耳其位于几个地质构造板块的交汇点，非洲板块向北移动，在爱琴海—塞浦路斯弧俯冲到北部的安纳托利亚板块之下，导致托罗斯山脉隆起；阿拉伯板块向西北移动，导致安纳托利亚板块向西移动，北部存在一个重要的剪切带，在那里，右旋北安纳托利亚断裂带（NAFZ）将安纳托利亚板块与黑海山脉分开；左旋东安纳托利亚断裂带（EAFZ）、左旋死海断裂带、比尔斯—扎格罗斯缝合带也对土耳其新构造框架的形成发挥了重要作用[2, 47]（图 1），由此产生了五个不同的构造区：（1）东安纳托利亚收缩构造区，位于 NAFZ 和 EAFZ 交界处以东，与东安纳托利亚高原相对应，该高原目前向东上升，海拔高达 3 000 m 以上；（2）北安纳托利亚构造区，位于 NAFZ 和东北安纳托利亚断裂带北部，平均海拔 500~700 m，由西向东上升，东西向缩短有限；（3）西安纳托利亚伸展构造区，南北向伸展导致爱琴海地区形成东西向地堑结构；（4）中安纳托利亚构造区，呈东北−西南缩短和西北−东南延伸，主要包括地中海沿岸的托罗斯山脉和安纳托利亚中部高原；（5）东南安纳托利亚构造区，东安纳托利亚高原被推覆在阿拉伯板块北部，收缩形成了一系列边界褶皱和逆冲断层[20, 47]。

土耳其境内从古生界到新生界各个时期地层发育较为齐全，寒武系岩性为花岗岩、片麻岩、云母片岩、石英岩、千枚岩和大理岩等，主要分布在色雷斯、西安纳托利亚门德列斯地块和东安纳托利亚比尔斯地块等；志留系地层主要岩性为砾岩、砂岩、石英岩、片岩和长石质岩等，主要分布在伊斯坦布尔地区；泥盆系分布广泛，主要岩性包括砂岩、石英岩、片岩和灰岩；石炭系、二叠系地层在北安纳托利亚 Zonguldak 盆地为陆相和海相，在南托罗斯地区一般为海相，主要岩性为灰岩、砂岩、砾岩等；中生界地层以灰岩、

白云质灰岩和泥灰岩为主，尤其以侏罗系、白垩系灰岩最为发育，主要分布在托罗斯山脉和黑海山脉；古近系以砾岩、泥灰岩、黏土岩和玄武岩等火山岩为主；新近系以砂岩、黏土岩、黏土质灰岩、湖相灰岩和石膏岩为主，主要分布在中安纳托利亚及西南安纳托利亚地区；第四系沉积分布广泛，包括冲积物、阶地沉积物和钙华等[49]。

2　岩溶发育的条件

碳酸盐岩地区的岩溶类型和发育程度受多种外部和内部因素的影响[50−53]。可溶岩的存在、地质结构、造山作用和构造是驱动岩溶发育的内动力，提供了促进或阻碍岩溶作用的基本框架，而气候则成为驱使岩溶发育的外动力因素，主要通过改变水的溶蚀能力来影响岩溶发育的速度、规模和类型。

2.1　可溶岩

土耳其约有 40% 的国土面积由石灰岩、白云岩和石膏等可溶岩组成，碳酸盐岩约占国土的三分之一[54]。从海拔高达 3 000 多米的高山地带到海滨地区，岩溶都有发育，托罗斯山脉地区是土耳其乃至整个地中海地区最大、最为发育的岩溶区，碳酸盐岩自寒武系至新近系都有产出，主要分布在中生代和新生代地层，以侏罗系、白垩系和新近系最为发育，在一些地方，碳酸盐岩总厚度超过 1 500 m[2]（图 2）。

土耳其石膏岩溶主要分布在安纳托利亚中部和东部，以 Sivas 盆地及其周边最为发育。Sivas 石膏岩溶盆地长 280 km，宽 55 km，在晚中新世 Hafik 地层发育，厚度达 750 m，局部被上新世和更新世沉积物覆盖，主要岩溶现象有洞穴、坡立谷、塌陷坑、落水洞、天生桥、岩溶泉等[17, 22,37, 55−56]。石膏属于蒸发沉积岩，溶解度明显高于碳酸盐岩，且溶解不受酸性来源限制（如二氧化碳、硫酸），表面和地下溶蚀地貌的形成和演化更为迅速，但由于其高溶解度和机械可蚀性，除非有利条件否则不适宜形成大面积露头的裸露岩溶地形。石膏岩机械强度低于碳酸盐地层，沿不连续面的快速溶解可以在短时间内显著降低岩体强度，地表易产生落水洞和塌陷坑[21, 34, 57]。

2.2　气　候

土耳其西南部地区属于地中海气候，夏季干燥温暖，冬季温和多雨，气温很少降到 0 ℃ 以下，Antalya 年平均气温为 18 ℃，沿海地区年降水量约 1 000 mm，在托罗斯山脉的南坡海拔较高的地方降雨量则更多[45]；安纳托利亚高原被高山环绕，气候更具大陆性

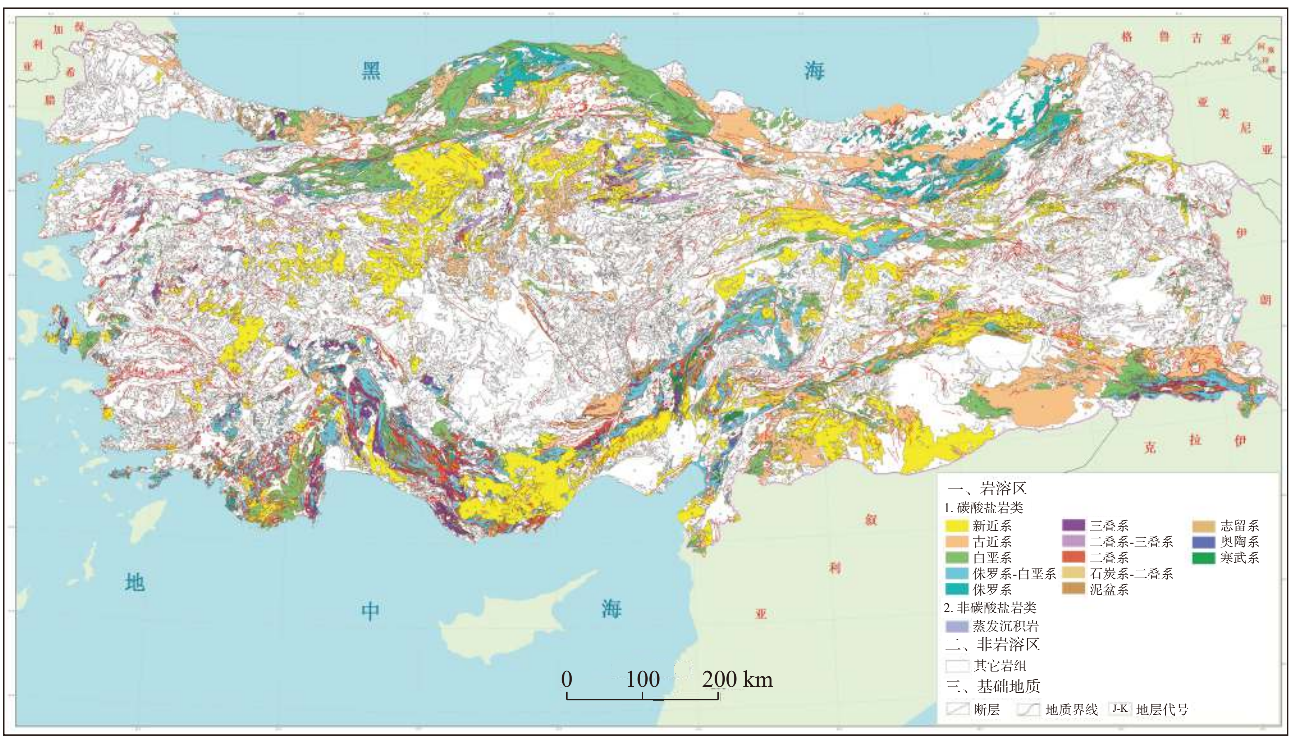

图 2　土耳其岩溶地质图

Fig. 2　Karst geological map of Turkey

特征，高原南部的 Konya 盆地年平均降雨量为 400 mm，降雨集中在 11 月至次年 5 月，年平均气温为 11.5 ℃[58]，高原北部 Sivas 省的 Hafik 地区冬季寒冷多雪，夏季炎热干燥，年平均降雨量为 424 mm，降雨一般发生在秋季[17]；靠近黑海的西北部城市 Zonguldak，气候温和潮湿，年平均降雨量为 1 150 mm，年平均气温为 14.5 ℃[59]。

2.3 构　造

土耳其所有地区都受到阿尔卑斯山造山运动和年轻的造山运动的影响。先前在加里东期和海西期造山作用期间发育的构造，在阿尔卑斯造山运动期间被再次折叠、再生或完全擦除，目前土耳其的大地构造线及地形都是由阿尔卑斯造山运动及其后的造山运动造成的[54]，岩溶发育强度超过了地中海其他地区，这是由于强烈的造山运动将碳酸盐岩抬高至海平面以上，从而在淡水和海洋之间行成强大的能量梯度。造山运动产生强烈的褶皱和断层作用，为初始水循环提供了径流通道，并在岩溶裂隙和管道的发育过程中为岩石溶解和次生孔隙的形成提供了机会。地形陡峭，高差巨大，成为气团运动的障碍，迫使气团显著上升并沉淀雨雪，从而为碳酸盐岩分布区地表和地下径流的快速渗透、循环和溶解提供充足的水动力条件[60]。

3 岩溶分区特征

根据构造特征，岩溶区被划分为四个单元：托罗斯山脉岩溶区、安纳托利亚东南岩溶区、安纳托利亚中部岩溶区、安纳托利亚西北岩溶区[61-62]（图 3）。

3.1 托罗斯山脉岩溶区

托罗斯山脉是阿尔卑斯造山运动期间由褶皱和逆冲断层作用形成的，是阿尔卑斯山向安纳托利亚的延伸，从爱琴海沿岸一直延伸到伊朗，托罗斯山脉岩溶区是土耳其最重要和最大的岩溶区[62]。

在地中海海岸和安纳托利亚中部之间的这一地区，碳酸盐岩的宽度接近 200 km，山峰高约 3 000 m，受构造运动影响，岩溶纵向发育，岩溶地貌包括岩溶洞穴、落水洞（图 4）、溶蚀洼地、坡立谷、天生桥和地下河等[10, 63]。该地区在地中海国家拥有最复杂的岩溶循环系统[61]，土耳其最长的洞穴 Pınargözü（8 500 m）和最深的洞穴 Peynirlikönü（1 429 m 深）都位于此处[1]。碳酸盐岩主要沉积于泥盆纪、二叠纪、三叠纪、侏罗纪、白垩纪和第三纪，侏罗系—白垩系灰岩最为发育，在一些剖面中，碳酸盐岩总厚度超过 1 000 m[61]。从中生代到全新世，灰岩受逆冲推覆作用沉积在片岩、砂岩、页岩等渗透率极低的地层上，构造运动产生的众多断裂成为导水通道，在灰岩与不透水地层的接触面上发育许多由中生代灰岩、第三纪灰岩和砾岩组成的大型岩溶泉，使得该区拥有世界上规模最大的喀斯特含水层和喀斯特温泉[64]。由于该区逆掩断层、上冲断层以及叠瓦状构造十分发育，三叠系、白垩系和第三系的片岩、砂岩、页岩等在碳酸盐岩层之间形成不透水屏障，切割纵向构造异常，根据 Herak 的分类，该区属于“切割造山岩溶”类型[62]。

东南托罗斯山脉（图 3）即东安托利亚地区，该区域为火山带，受挤压构造作用自中新世持续隆升，该地区碳酸盐岩主要位于二叠系、侏罗系和新近系地层，由于存在连续且较厚的不可溶岩石，岩溶横向、纵向都不发育[2]。

3.2 安纳托利亚东南岩溶区

结合托罗斯南部的区域地质特征，该区域可分为边缘褶皱和稳定地台（图 5）。稳定地台是东南安纳托利亚典型的平坦高原地区。在 Gaziantep 和 Urfa 地区，黏土质石灰岩显示出较差的岩溶作用。在边缘褶皱带，即碰撞板块（阿拉伯地台向北部的安纳托利亚板块移动）之间的边缘地带，该区域构造收缩明显，呈大体东西向延伸的褶皱和垂直于褶皱的正断层，挤压构造减缓了岩溶作用的强度，该区域岩溶发育主要受河流的抬升切割侵蚀作用，幼发拉底河和底格里斯河的河床是该区域的主要侵蚀基底，主要泉水大多出露在河床和形成地堑的正断层中[65]。岩溶以横向发育为主，类似托罗斯山脉地区的大型洞穴在本区域内是罕见的，地下水由北向南流动，在土耳其东南边界附近出露大型泉群，大型岩溶泉主要发育于始新世石灰岩，如土耳其—叙利亚边界的 Rasal-Aïn 泉，土耳其一侧流量为 1 $m^3·s^{-1}$，叙利亚一侧为 43 $m^3·s^{-1}$。由于该区受挤压构造影响，岩溶纵向不发育，主要发育在地表浅层，根据 Herak 的分类，安纳托利亚东南部的岩溶属于“造山表生岩溶”[62]。

3.3 安纳托利亚中部岩溶区

该区南部为托罗斯山脉，北部为北安纳托利亚

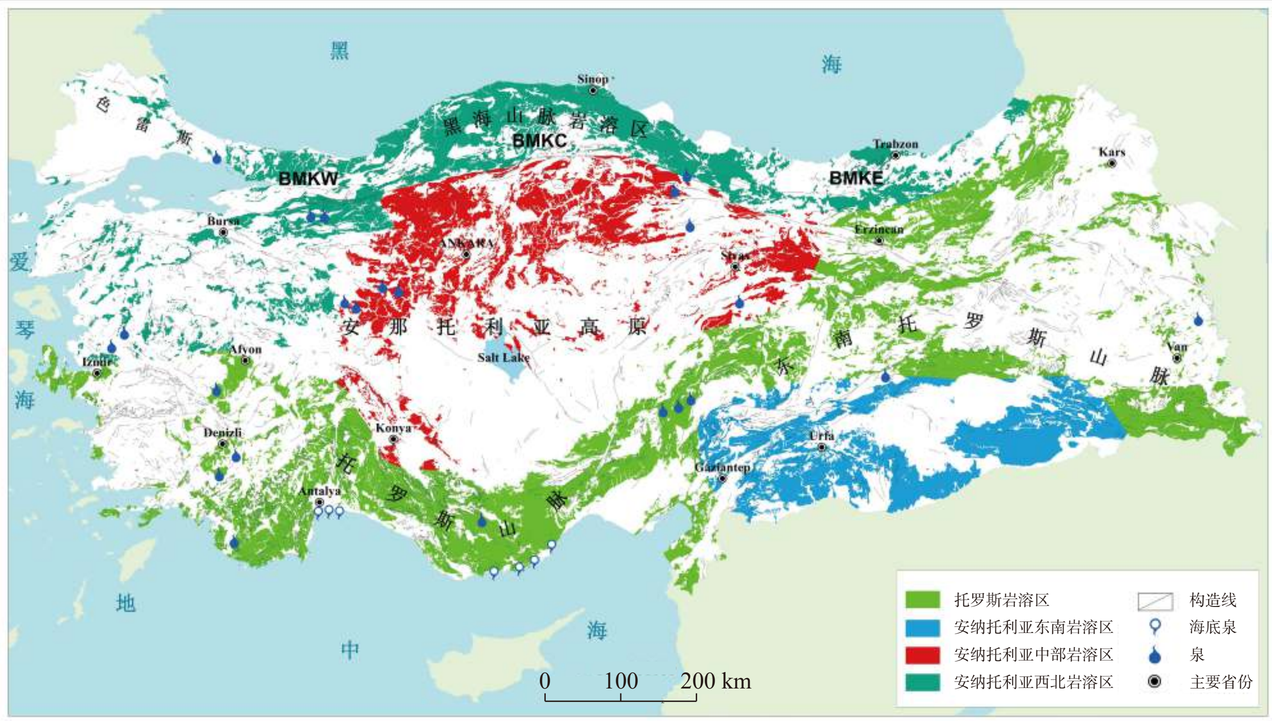

图 3　土耳其岩溶分区图(修改自 Eroskay[61] 和 Gültekin[62])

Fig. 3　Karst distribution in Turkey (Modified from Eroskay[61] 和 Gültekin[62])

图 4　托罗斯山脉大型落水洞[1]

Fig. 4　Large sinkholes in the Taurus mountains[1]

图 6　Sivas 省石膏岩溶[22]

Fig. 6　Gypsum karst in Sivas Province[22]

图 5　边缘褶皱带的岩溶地貌[20]

Fig. 5　Karst landforms of marginal fold belts[20]

断裂,岩溶主要发育于二叠系、侏罗系、白垩系、新近系碳酸盐岩,渐新世、晚中新世蒸发岩中(如 Sivas 省石膏岩(图 6))也有分布,主要岩溶地貌有洞穴、坡立谷、塌陷坑、落水洞、天生桥、岩溶泉等。该地区可识别出两种不同的岩溶带,其中一个是托罗斯带较老的侏罗系、白垩系灰岩,位于盆地南部和西部边缘,另一个是缓倾斜的湖相新近系灰岩和蒸发岩,位于盆地中部及北部。大型岩溶泉水主要产自古生界和中生界灰岩,部分小型泉水产自新近系灰岩,其中一些大泉如 Karaman - Ayrancı −Akcaşehir 泉

(3 $m^3 \cdot s^{-1}$), Ereğli - Bor 泉(6.5 $m^3 \cdot s^{-1}$), İvriz 泉(5.7 $m^3 \cdot s^{-1}$)。从地貌上看,安纳托利亚中部地区是一个以高山为界的封闭盆地,平均海拔约 1 200 m,盆地底部形成盐湖,岩溶地貌受到构造影响,根据 Herak 的分类,安纳托利亚中部岩溶区对应于“造山盆地岩溶”[61]。

3.4 安纳托利亚西北岩溶区

该区域包括色雷斯山脉以及黑海沿岸区域。在色雷斯地区,由二叠系—三叠系大理岩组成的 Itranca 地块与 Itranca 地块南部和西部的始新世灰岩形成了一条北西−南东向延伸带,始新世碳酸盐岩层序较薄,厚度大约 100~150 m,灰岩平行于伊斯特兰卡地块等斜褶皱,平均倾角为 20°~30°,该地区以古岩溶为主,40~160 m 高度发育单层水平洞穴,240~450 m 高度发育多层水平洞穴。黑海山脉岩溶区(BMK)位于土耳其最北部,自西向东分为西部(BMKW)、中部(BMKC)和东部(BMKE)。黑海山脉西部岩溶发育在石炭系、侏罗系、白垩系以及始新世灰岩,以覆盖型岩溶和浅层岩溶为主,落水洞和溶蚀洼地分布广泛;黑海山脉东部地区以古岩溶为主,岩溶作用深度较浅,洞穴系统不发育;黑海山脉中部岩溶位于北安那托利亚地区的北部,以弧形的形式指向黑海,该区岩溶作用深度在土耳其仅次于托罗斯山脉岩溶区,广泛发育高原型岩溶,部分埋藏岩溶和深层溶洞体系,主要岩溶地貌包括洞穴、坡立谷、落水洞、溶蚀洼地和峡谷等[66](图 7),岩溶主要发育于二叠系—三叠系变质岩中的透镜状大理岩和上覆的侏罗系—白垩系浅海灰岩,且受新构造运动影响明显,根据 Herak 的分类,此处岩溶可对应为“透镜状造山岩溶”[62]。

4 主要岩溶现象

4.1 岩溶泉

岩溶泉主要分布在托罗斯山脉、安纳托利亚中部以及安纳托利亚西北地区。托罗斯山脉岩溶区许多地方发育由中生代灰岩、第三纪灰岩和砾岩组成的大型岩溶泉(表 1)。Dumanlı泉位于 Antalya 省,从峡谷里的一个洞穴流出,其出口点海拔 62 m,高出河面约 5 m,离河岸不超过 10 m,泉水平均流量估计约为 50 $m^3 \cdot s^{-1}$,年流量约为 1.6×10^9 m^3,是土耳其最大的岩溶泉[64](图 8)。

图 7 黑海山脉地区的坡立谷[66]

Fig. 7 A polje in the mountainous area of western Black Sea[66]

表 1 托罗斯山脉岩溶区大型岩溶泉的分布及其平均流量[64]

Table 1 Distribution of large karst springs and their average flow rates in the karst area of Taurus[64]

省份	泉名称	流量/$m^3 \cdot s^{-1}$
Izmir	Halkapınar Spring	1.2
Izmir	Bakrçay plain springs	1.2
Aydin	K. Menderes plain springs	2.0
Aydin	B. Menderes plain springs	1.0
Antalya	Finike-Tekke and Salur Springs	3.0
Antalya	Elmalı-Akçay-Demre plains springs	7.0
Antalya	Bogaçay plain springs	2.5
Antalya	Kırkgöz Springs	20.0
Antalya	Düdenbası Spring (underground river)	10.0
Antalya	Dumanlı	50.0
Isparta	Hoyran, Gelendost-Yalvaç plains springs	1.0
Afyon	Akarçay basin springs	1.5
Içel	Gilindire-Soguksu spring and Gözce plain springs	2.0
Içel	Silifke and Erdemli Springs	5.0
Maras	Maras plains springs	8.0
Maras	Göksun plain springs	8.0
Hatay	Asi basin springs	3.0
Mus	Mus plain springs	0.8

4.2 钙 华

钙华主要分布在托罗斯山脉的 Antalya 省、Denizli 省,东安纳托利亚 Başkale 省以及安纳托利亚中部的 Sivas 省。Antalya 省钙华高原面积约为 615 km^2,由中生代碳酸盐中排出的泉水在泉口处发生 CO_2 的物理和生物脱气导致钙华沉淀,平均厚度约为 300 m[63, 67]。Denizli 省的棉花堡温泉产生于断层活动,下覆地层有古生代大理岩,中生代结晶灰岩,上新世灰岩、白云灰岩,其高原流水及温泉水导致温

图 8　Dumanlı泉
（https://link.springer.com/article/10.1007/s12665-015-4298-6/figures/3）
Fig. 8　Dumanlı spring

图 9　棉花堡钙华（https://cn.bing.com/images/search?q=%e6%a3%89%e8%8a%b1%e5%a0%a1&form=HDRSC2&first=1）
Fig. 9　Travertine in Pamukkale

泉盆地中形成钙华沉淀[9, 68], 现已成为闻名世界的旅游景区(图 9)。

4.3　岩溶峡谷

岩溶峡谷主要分布在托罗斯山脉及地中海区域、黑海和东安纳托利亚。位于托罗斯山脉的 Köprülü 峡谷长 14 km, 深 100 m, 是土耳其最长的峡谷, 1973 年被宣布为国家公园, 在这里可以欣赏到特色的岩溶景观及丰富的生物多样性[69](图 10)。

图 10　Köprülü峡谷（https://antalyatouristinformation.com/things-to-do/canyon/koprulu/）
Fig. 10　Köprülü canyon

4.4　岩溶塌陷

岩溶塌陷主要分布在安纳托利亚中部的 Sivas 省及 Konya 省, Sivas 省的石膏岩相对于碳酸盐岩具有更高的溶解度和更低的机械强度, 地表易产生落水洞和塌陷坑, 据相关资料统计, 在 Sivas 周边 2 820 km^2 的地区分布着 600 余个的塌陷坑[21]。Konya 盆地东部发育新近系湖泊相灰岩和黏土质灰岩[70], 由于过量开采地下水, Karapinar 地区地下水位从 1970 年 10 月至 2010 年 4 月下降了 64 m, 导致 2 363 km^2 的地区分布有 182 个塌陷坑, 直径从几米到几百米不等[71]; 在农业活动密集区域, 5 115 hm^2 的土地上钻探了 109 口灌溉井, 长期过度开采地下水导致其周围 100 km^2 区域内分布有 50 个塌陷坑[7](图 11)。

4.5　洞　穴

据统计, 土耳其有超过 20 000 个未知洞穴分散

图 11　Karapinar 地区塌陷坑[7]
Fig. 11　Sinkholes in the Karapinar area[7]

在岩溶地区[1](图 12, 表 2)。为此,土耳其开展了大量的岩溶水文、地质、地貌研究,通过地球化学和地球物理调查来研究这些地区的岩溶地质条件,近年来洞穴研究的数量有所增加。

土耳其碳酸盐岩洞穴主要集中在靠近地中海的托罗斯山脉、黑海中西部岩溶区和色雷斯岩溶区,安

图 12　托罗斯山脉 Altınbeşik 洞穴

(https://en.antaliy.com/altinbesik-cave/)

Fig. 12　Altınbeşik cave in the Taurus mountains

表 2　土耳其最长的几个洞穴(截止到 2020 年)[1]

Table 2　Longest caves of Turkey (by the end of 2020)[1]

洞穴名称	省份	长度/m
Pınargözü Cave	Yenisarbademli, Isparta	8 500
Insuyu Cave	Burdur	8 350
Tilkiler Cave	Manavgat, Antalya	6 818
Kızılelma Cave	Zonguldak	6 630
Yaylacık-Inilti Pazan System	Gündogmus, Antalya	5 929
Bulak Mencilis Cave	Karabük, Safanbolu	5 250
Altınbesik Cave	Akseki, Ürünlü,Antalya	5 119
Ayvaini Cave	Ayvaköy, Bursa	4 866
lkigöz Cave	Catalca, Istanbul	4 816
Morca Sinkhole	Anamur, lcel	4 068
Yazören Cave	Yazören, Balikesir	3 554
Cukurpiar Sinkhole	Anamur, lçel	3 350
Gökgöl Cave	Erçek, Zonguldak	3 350
Kuzgun Sinkhole	Nigde	3 187
Dupnisa Cave	Sarpdere, Kırklareli	3 150
Peynirlikönü Sinkhole	Anamur, lçel	3 118
Düdenagzı Sinkhole	Basyayla, Karaman	2 528
Susuz Cave	Seydisehir, Konya	2 303
Tınaztepe Caves	Seydisehir, Konya	2 195
Kızılin Cave	Burdur	2 176
Saçayagı Cave	Gazipasa, Antalya	2 125

纳托利亚中部地区虽发育石膏洞穴,但数量有限且规模较小。由于地质和气候条件的差异,土耳其地中海地区的洞穴和黑海地区的洞穴表现出不同的形态特征。

(1)色雷斯岩溶区以古岩溶为主,海拔 40~160 m 发育单层水平洞穴,240~450 m 高度发育多层水平洞穴;

(2)黑海西部岩溶区白云岩和火山岩分布广泛,岩溶纵向不发育,主要在海拔 350 m 以下发育多期次水平洞穴;

(3)黑海中部岩溶区被北安纳托利亚断裂带构造线上发育的 Kızılırmak 支流深切,发育垂向洞穴,部分深度超过 200 m[66],但由于石灰岩厚度较薄,最深的溶洞深度小于 300 m [1]。

(4)靠近地中海的托罗斯山脉岩溶区逆掩断层、上冲断层等构造十分发育,部分地区碳酸盐岩厚度超过 1 000 m,多发育垂向洞穴,且在海拔 3 000 m 的高山均有洞穴发育。土耳其最长的洞穴 Pınargözü(8 500 m 长)和最深的洞穴 Peynirlikönü(1 429 m 深)都位于该岩溶区。

截至 2019 年,土耳其已知深度超过 200 m 的洞穴有 52 个,其中 43 个位于地中海附近的托罗斯山脉岩溶区,7 个位于黑海中部岩溶区;长度超过 1 000 m 的洞穴共有 62 个,其中 34 个位于地中海附近的托罗斯山脉岩溶区,16 个位于黑海中、西部以及色雷斯岩溶地区[66](表 2, 表 3)。

5　主要资源

5.1　水资源

土耳其年平均降水量约为 643 mm,相当于总水量 5 010 亿 m^3,平均径流系数为 0.37[46],年总径流量约 1 860 亿 m^3,可利用水量 1 100 亿 m^3,其中地表水 950 m^3,地下水 120 亿 m^3,另 30 亿 m^3 水量是从其他国家流入。虽然水资源蕴藏量在欧洲排行第三,但人均水资源量约 1 690 m^3/人,与伊拉克和叙利亚相当,面临水资源压力[72-73]。

土耳其岩溶水资源的经济意义是巨大的。到 1976 年,土耳其仅利用了约 11% 的水力发电潜力,估计每年超过 1 000 亿 kW·h,土耳其最大的大坝 Keban 大坝(1 240 MW)就坐落于岩溶山区;土耳其

表 3　土耳其最深的几个洞穴（截止到 2020 年）[1]

Table 3　Deepest caves of Turkey (by the end of 2020)[1]

洞穴名称	省份	深度/m
Peynirlikönü Sinkhole	Anamur, Içel	1 429
Kuzgun Sinkhole	Nigde	1 400
Morca Sinkhole	Anamur, Içel	1 210
Cukurpmar Sinkhole	Anamur, Içel	1 196
Kuyukule Sinkhole	Dedegöl, Isparta	832
Kes Sinkhole	Kahramanmaras	728
Subatagi Sinkhole	Yahyal, Kayseri	643
Sütlük Sinkhole	Pozanti, Adana	640
Düdenagzı Sinkhole	Basyayla, Karaman	612
Cem Sinkhole	Tomarza, Kayseri	605
Yılanlıyurt Sinkhole	Aladag	603
Yaylacık -Inilti Pazan System	Gündogmus, Antalya	595
Kocadag Sinkhole	Anasultan, Kütahya	458
Pınargözü Cave	Yenisarbademli, Isparta	440
Düdenyayla Sinkhole	Beysehir, Konya	416
Athar Sinkhole	Gözne, Içel	410
Camlıköy Sinkhole	Pozantı, Adana	379
Macar Sinkhole	Gazipasa, Antalya	356
Bucakalan Sinkhole	Akseki, Antalya	345
Ölü Köpek Sinkhole	Akseki, Cevizli,Antalya	340
Düdencik Sinkhole	Akseki, Cevizli, Antalya	330

许多城市经济完全依赖于岩溶地下水资源，Izmir 市和 Antalya 市用水来自岩溶含水层井水及泉水，土耳其地中海沿岸的棉花田灌溉也依赖于岩溶泉水[74]。

5.2　土地资源

土耳其位于阿尔卑斯—喜马拉雅造山带，地形崎岖。在海拔 1 000 m 以下和 1 000 m 以上分布的地表面积的占比分别为 44.1% 和 55.9%。1945 年统计数据显示农业用地占 18.85%，森林用地占 13.55%，牧场和草地用地占 50.19%，其他地区用地占 17.41%；由于土耳其通过立法来保护森林，到 2017 年森林用地增长了一倍，占 27.81%，而城市化进程的快速发展，到 2017 年其他用地占 23.45%，农业用地占 29.99%，牧场和草地占比减少至 18.75%[75]。 土耳其森林主要分布在托罗斯山脉、黑海山脉以及西安托利亚沿海山脉，同时是岩溶集中分布的地区，其中 42% 为针叶林，53.3% 为阔叶林，拥有超过 450 种乔木和灌木，生物多样性十分丰富[76]。

5.3　地热资源

土耳其是世界上地热资源最丰富的国家之一，主要原因是其位于欧亚板块南缘，受阿拉伯板块和非洲板块的北向俯冲，处于弧后伸展的构造应力区，地壳持续拉张减薄且构造断层发育，土耳其境内分布超过 600 个温泉，温度最高可达 100 ℃ 以上[77]。据估土耳其的水热型地热资源潜力（0~4 km）为 60 000 MW，78% 左右集中在安纳托利亚西部，9% 在安纳托利亚中部，5% 在安纳托利亚东部[78]。低焓或中焓地热资源约占 90%，适合直接利用，地热发电潜力（0~4 km）为 4 500 MW[79]。

5.4　油气资源

土耳其的油气勘探开发活动始于 19 世纪 80 年代末，到 2021 年，全国共有 250 多家从事油气勘探的公司，将近 200 家为外国公司。石油和天然气主要分布于东南部油气区、南部的阿达纳盆地、西部的色雷斯盆地，以及黑海沿岸近海区。其中黑海海域石油资源量初步估计为 10×10^8 t，天然气 $8\ 000\times10^8\ m^3$。地中海海域天然气资源潜力前景广阔，但勘探程度目前相对较低[80]。

5.5　矿产资源

土耳其矿产资源多样性位居世界第 10 位，矿产资源生产能力位居第 28 位，拥有 77 种全世界可交易的矿产资源，是世界上为数不多几个能够满足自身原材料供应需求的国家之一。大理石储量占世界的 40%[44, 81]，根据世界贸易组织和联合国数据，2018 年土耳其占世界大理石出口总量的 38%[82]。

5.6　景观资源

土耳其拥有岩溶洞穴、峡谷、河流、湖泊、瀑布和温泉等丰富的自然景观，是世界著名的旅游胜地。Köprülü国家公园位于托罗斯山脉，拥有土耳其最长的峡谷，峡谷里植被繁茂，空气清新，飞瀑神泉比比皆是，被认为是世界上最好的漂流地点；中安纳托利亚的 Sivas 地区拥有坡立谷、岩溶洞穴、岩溶湖泊、温泉等景观，著名的 Fish 温泉因其泉水独特的作用已被用于治疗牛皮癣[69]；棉花堡温泉钙华景观由多层阶梯状钙华堤组成，是远近闻名的温泉度假胜地，被列为世界文化、自然双重遗产；Altınbeşik 洞穴距离 Antalya 市 167 km，于 1994 年被列为国家公园，洞穴内钙质沉积物绚丽多姿，如水晶玉石，美不胜收，

是土耳其第一大地下湖。

6 结 语

土耳其岩溶面积占国土面积的 40%,其中碳酸盐岩约占国土面积的三分之一。厚且纯的碳酸盐岩、温和多雨的地中海气候以及造山运动产生强烈的褶皱和断裂是其岩溶发育的主要原因。托罗斯山脉岩溶区是土耳其乃至整个地中海国家岩溶最为发育的地区,碳酸盐岩主要分布在中生代和新生代的地层,以侏罗系、白垩系和新近系最为发育,主要地貌有岩溶洞穴、落水洞、溶蚀洼地、坡立谷、大泉、天生桥、地下河流和海底泉。土耳其大理石、地热、石油、天然气等岩溶资源丰富,且有丰富的大泉、洞穴、峡谷、钙华等岩溶景观,开发利用前景广阔,亟待开展详细的岩溶水文地质调查工作。

参考文献

[1] Ali Yamaç E G, Ezgi Tok, Koray Törk. Cave and karst systems of the World[M]. Berlin, Germany: Springer Nature, 2021.

[2] Gilli E. Karst areas of Turkey[J]. Caves and Karst of Turkey-Volume 2, 2022: 55-65.

[3] Katsanou K, Maramathas A, Sağır Ç, Kurtuluş B, Baba A, Lambrakis N. Determination of karst spring characteristics in complex geological setting using MODKARST model: Azmak Spring, SW Turkey[J]. Arabian Journal of Geosciences, 2023, 16(1): 4.

[4] Şener A, Yolcubal İ, Sanğu E. Determination of recharge, storage and flow characteristics of a karst aquifer using multi-method approaches (Kocaeli, Turkey)[J]. Hydrogeology Journal, 2020, 28(6): 2141-2157.

[5] Yüce G. Determination of the recharge area and salinization degree of karst springs in the Lamas Basin (Turkey)[J]. Isotopes in Environmental and Health Studies, 2005, 41(4): 391-404.

[6] Acikel S, Ekmekci M. Distinction of multiple groundwater systems in a coastal karst spring zone in SW Turkey by hydrochemical and isotopic characteristics[J]. Bulletin of Engineering Geology and the Environment, 2021, 80(7): 5781-5795.

[7] Günay G, Çörekçioğlu İ, Övül G. Geologic and hydrogeologic factors affecting sinkhole (obruk) development in Central Turkey[J]. Carbonates and Evaporites, 2011, 26(1): 3-9.

[8] Yetiş R, Atasoy A D, Demir Yetiş A, Yeşilnacar M İ. Hydrogeochemical characteristics and quality assessment of groundwater in Balikligol Basin, Sanliurfa, Turkey[J]. Environmental Earth Sciences, 2019, 78(11): 331.

[9] Günay G. Karst hydrogeology of Pamukkale Thermal Springs, Denizli, Turkey[J]. Caves and Karst of Turkey-Volume 2, 2022: 81-84.

[10] Elhatip H, Günay G. Karst hydrogeology of the Kaş-Kalkan springs along the Mediterranean coast of Turkey[J]. Environmental Geology, 1998, 36(1-2): 150-158.

[11] Günay G. Karst springs of Turkey: Hydrogeology of the Kirkgözler karst springs, Antalya[J]. Caves and Karst of Turkey-Volume 2, 2022: 67-73.

[12] Ekmekci M. Pesticide and nutrient contamination in the Kestel polje–Kirkgoz karst springs, Southern Turkey[J]. Environmental Geology, 2005, 49(1): 19-29.

[13] Bayari C S, Ozyurt N N, Kilani S. Radiocarbon age distribution of groundwater in the Konya Closed Basin, central Anatolia, Turkey[J]. Hydrogeology Journal, 2009, 17(2): 347-365.

[14] Ozyurt N, Bayari C. Temporal variation of chemical and isotopic signals in major discharges of an alpine karst aquifer in Turkey: Implications with respect to response of karst aquifers to recharge[J]. Hydrogeology Journal, 2008, 16(2): 297-309.

[15] G Günay, N Güner, Trk K. Turkish karst aquifers[J]. Environmental Earth Sciences, 2015, 74(1): 217-226.

[16] Ekmekci M, Nazik L. Evolution of Golpazari-huyuk karst system (Bilecik-Turkey): Indications of morpho-tectonic controls [J]. International Journal of Speleology, 2004, 33(1-4): 49.

[17] Dogan U, Ozel S. Gypsum karst and its evolution east of Hafik (Sivas, Turkey)[J]. Geomorphology, 2005, 71(3-4): 373-388.

[18] Lewin J, Woodward J. 10 karst geomorphology and environmental change[J]. The Physical Geography of the Mediterranean, 2009: 287-318.

[19] Catherine Kuzucuoğlu. Geomorphological landscapes in the Konya Plain and surroundings[J]. Landscapes and Landforms of Turkey, 2019.

[20] Catherine Kuzucuoğlu, Şengör A M C, Attila Çiner. The tectonic control on the geomorphological landscapes of Turkey[J]. Landscapes and Landforms of Turkey, 2019.

[21] Ergin Gökkaya, Francisco Gutiérrez, Mateja Ferk, Tolga Görüm. Sinkhole development in the Sivas gypsum karst, Turkey[J]. Geomorphology, 2021, 386: 107746.

[22] Gökkaya E. Poljes in the Sivas gypsum karst, Turkey[J]. Geomorphology, 2022, 417: 108451.

[23] Aydn Topu T T, Osman Seyyar, Nurcan Demircan, Hayriye Karabulut. A new species of Troglohyphantes (Araneae: Linyphiidae) from a Turkish cave[J]. Open Journal of Animal Sciences, 2014, 4(2): 85-87, 89-91.

[24] Candiroglu B, Gungor N D. Cave ecosystems: Microbiological view[J]. European Journal of Biology, 2017, 76(1): 36-42.

[25] Klimchouk A, Bayari S, Nazik L, Törk K. Glacial destruction of cave systems in high mountains, with a special reference to the Aladaglar massif, Central Taurus, Turkey[J]. Acta Carsologica, 2006, 35(2): 111-121.

[26] Ozturk S. Algal flora of an extremophile ecosystem: Kaklik Cave (Denizli, Turkey)[J]. Maejo International Journal of Science &

Technology, 2021, 15(2): 173-186.

[27] Ozyurt N N, Bayari C S. Evolution of noble gas and water isotopes along the regional groundwater flow path of the Konya Closed Basin, Turkey[J]. International Journal of Speleology, 2018, 47(3): 333-342.

[28] Rachid N A, Güngör N D. Major impacts of caving activities on cave microbial diversity: Case study of Morca Cave, Turkey[J]. International Microbiology, 2023, 26(2): 179-190.

[29] Ulcay S, Kurt O, Akcora C M, Ozturk M. Environmental monitoring in the Kaklik Cave (Denizli, Turkey)[J]. Natural Science, 2012, 4(3): 159-165.

[30] Yamaç M, Işik K, Şahi̇n N. Numerical classification of streptomycetes isolated from karstic caves in Turkey[J]. Turkish Journal of Biology, 2011, 35(4): 473-484.

[31] Şener A, Pekşen E, Yolcubal İ. Application of square array configuration and electrical resistivity tomography for characterization of the recharge area of a karst aquifer: A case study from Menekşe karst plateau (Kocaeli, Turkey)[J]. Journal of Applied Geophysics, 2021, 195: 104474.

[32] Gemici U, Somay M, Akar T, Tarcan G. An assessment of the seawater effect by geochemical and isotopic data on the brackish karst groundwater from the Karaburun Peninsula (Izmir, Turkey)[J]. Environmental Earth Sciences, 2016, 75(12): 1008.

[33] Özdemir A. Defining groundwater resource protection zones in aquifers using stable isotope analysis: A case study from the Namazgah Dam Basin in Turkey[J]. Environmental Earth Sciences, 2019, 78(16): 509.

[34] Özel S, Darıcı N. Environmental hazard analysis of a gypsum karst depression area with geophysical methods: A case study in Sivas(Turkey)[J].EnvironmentalEarthSciences,2020,79(5):1-14.

[35] Balkaya Ç, Göktürkler G, Erhan Z, Ekinci Y L. Exploration for a cave by magnetic and electrical resistivity surveys: Ayvacık Sinkhole example, Bozdağ, İzmir (western Turkey)[J]. Geophysics, 2012, 77(3): B135-B146.

[36] Jacobson M J, Flohr P, Gascoigne A, Leng M J, Sadekov A, Cheng H, Edwards R L, Tüysüz O, Fleitmann D. Heterogenous Late Holocene climate in the Eastern Mediterranean: The Kocain cave record from SW Turkey[J]. Geophysical Research Letters, 2021, 48(20): e2021GL094733.

[37] Drahor M G. Identification of gypsum karstification using an electrical resistivity tomography technique: The case-study of the Sivas gypsum karst area (Turkey)[J]. Engineering Geology, 2019, 252: 78-98.

[38] Karaman A, Karadayılar T. Identification of karst features using seismic P-wave tomography and resistivity anisotropy measurements[J]. Environmental Geology, 2004, 45(7): 957-962.

[39] Sağır Ç, Kurtuluş B, Soupios P, Ayrancı K, Düztaş E, Aksoy M E, Avşar Ö, Erdem G, Pekkan E, Canoğlu M C, Kaka S I, Razack M. Investigating the structure of a coastal karstic aquifer through the hydrogeological characterization of springs using geophysical methods and field investigation, Gökova Bay, SW Turkey[J]. Water, 2020, 12(12): 3343.

[40] Kilic G, Eren L. Neural network based inspection of voids and karst conduits in hydro−electric power station tunnels using GPR(Article)[J].JournalofAppliedGeophysics,2018,151:194-204.

[41] Bayari C S, Pekkan E, Ozyurt N N. Obruks, as giant collapse dolines caused by hypogenic karstification in central Anatolia, Turkey: Analysis of likely formation processes[J]. JOM: JournaloftheMineralsMetals&MaterialsSociety,2009,17(2):327-345.

[42] Jex C N, Phipps S J, Baker A, Bradley C. Reducing uncertainty in the climatic interpretations of speleothem $\delta^{18}O$[J]. Geophysical Research Letters, 2013, 40(10): 2259-2264.

[43] René Putiška M M, Isik Yilmaz, Dominik Niemiec, Xianfeng Cheng, Ivan Dostal, Ján Kubáč. Surface geophysical methods used to verify the karst geological structure in the built-up area: A case study of specific engineering-geological conditions[J]. Acta Geologica Sinica-English Edition, 2021, 95(5): 1763-1770.

[44] 宋国明. 土耳其矿业投资环境[J]. 国土资源情报, 2014(10): 43-47.
SONG Guoming. Mining investment environment in turkey[J]. Land and Resources Information, 2014(10): 43-47.

[45] Dinçer T, Payne B R. An environmental isotope study of the south-western karst region of Turkey[J]. Journal of Hydrology, 1971, 14(3-4): 233-258.

[46] M 贝阿济特. 土耳其水资源规划和开发及管理[J]. 水利水电快报, 1998(18): 22-27.

[47] Bozkurt E, Mittwede S K. Introduction to the geology of Turkey: Asynthesis[J].InternationalGeologyReview,2001,43(7):578-594.

[48] Raja N B, Aydin O, Iek H, Türkolu N. A reconstruction of Turkey's potential natural vegetation using climate indicators[J]. Journal of Forestry Research, 2019, 30(6): 2199-2211.

[49] Wolf D, Rotter V. A general review of the geology of Turkey[J]. Bulletin of the Mineral Research and Exploration, 2018, 48: 2018.

[50] 康小兵, 杨四福, 管振德, 张文发, 许模. 川西高原巴塘地区可溶岩地层分布与岩溶地貌发育特征[J]. 中国岩溶, 2021, 40(3): 381-388.
KANG Xiaobing, YANG Sifu, GUAN Zhende, ZHANG Wenfa, XU Mo. Distribution of soluble rock strata and development of karst landforms in the Batang area, west Sichuan plateau[J]. Carsologica Sinica, 2021, 40(3): 381-388.

[51] 李芳涛, 李华明, 胡志平, 陈南南, 晏长根. 峨汉高速廖山隧道岩溶发育规律及其工程效应浅析[J]. 中国岩溶, 2020, 39(4): 592-603.
LI Fangtao, LI Huangming, HU Zhiping, CHEN Nannan, YAN Changgen. Features of karst development and geotechnical effects in the Liaoshan tunnel on the E-Han expressway[J]. Carsologica Sinica, 2020, 39(4): 592-603.

[52] 吴远斌, 刘之葵, 殷仁朝, 杨建兴, 罗伟权, 雷明堂, 戴建玲, 潘宗源. 湖南怀化盆地岩溶发育特征与分布规律[J]. 中国岩溶, 2022, 41(5): 759-772,807.
WU Yuanbin, LIU Zhikui, YIN Renchao, YANG Jianxing, LUO

Weiquan, LEI Mingtang, DAI Jianling, PAN Zongyuan. Karst development characteristics and distribution law in Huaihua basin, Hunan Province[J]. Carsologica Sinica, 2022, 41(5): 759-772,807.

[53] 姜文, 柏道远, 尹欧, 杨帆, 彭祖武, 钟响, 李彬, 李银敏. 湘中灰山港—煤炭坝地区岩溶发育特征及其构造控制[J]. 中国岩溶, 2022, 41(1): 1-12.
JIANG Wen, BAI Daoyuan, YIN Ou, YANG Fan, PENG Zuwu, ZHONG Xiang, LI Bin, LI Yinmin. Characteristics of karst development and its structural control in the Huishangang-Meitanbaareaofcentral Hunan[J].CarsologicaSinica,2022,41(1):1-12.

[54] Günay G, Törk K, Güner İ N. Karst of Turkey[J]. Caves and Karst of Turkey-Volume 2, 2022: 1-5.

[55] Yĭlmaz I Ş. GIS based susceptibility mapping of karst depression in gypsum: A case study from Sivas basin (Turkey)[J]. Engineering Geology, 2007, 90(1-2): 89-103.

[56] Uğur Doğan, Serdar Yeşilyurt. Gypsum karst landscape in the Sivas Basin[J]. Landscapes and Landforms of Turkey, 2019.

[57] Bayari C S, Pekkan E, Ozyurt N N. Obruks, as giant collapse dolines caused by hypogenic karstification in central Anatolia, Turkey: Analysis of likely formation processes[J]. Hydrogeology Journal, 2009, 17(2): 327-345.

[58] Bayarı C S, Özyurt N N, Törk A K, Avcı P, Güner İ N, Pekkan E. Geodynamic control of hypogene karst development in central Anatolia, Turkey[J]. Hypogene Karst Regions and Caves of the World, 2017: 449-462.

[59] S K. How Roman engineers selected their water supplies[J]. Water Management, 2007, 160(4): 249-253.

[60] Elhatipc H. The influence of karst features on environmental studiesinTurkey[J].EnvironmentalGeology,1997,31(1-2):27-33.

[61] Eroskay S O. Engineering properties of carbonate rocks and karst regions in Turkey[J]. Bulletin of Engineering Geology and the Environment, 1982, 25(1): 61-65.

[62] Günay G. Turkey's karst and water resources[J]. Caves and Karst of Turkey-Volume 2, 2022: 7-15.

[63] Günay G. Karst of Antalya travertine, Southwest of Turkey[J]. Caves and Karst of Turkey-Volume 2, 2022: 17-25.

[64] Günay G. Chapter 10.6−Case Study: Geological and hydrogeological properties of Turkish karst and major karstic springs[J]. Groundwater Hydrology of Springs, 2010: 479-497.

[65] Ekmeci M. Review of Turkish karst with emphasis on tectonic and paleogeographic controls[J]. Acta Carsologica, 2016, 32(2).

[66] Lütfi Nazik, Murat Poyraz, Mustafa Karabıyıkoğlu. Karstic landscapes and landforms in Turkey[J]. Landscapes and Landforms of Turkey, 2019.

[67] Özçelikc M. Foundation investigations and design in a karst terrain for the Antalya aquarium complex, Turkey[J]. Quarterly Journal of Engineering Geology and Hydrogeology, 2015, 48(3-4): 204-211.

[68] 董发勤, 代群威, 赵玉连, 陈木兰, 饶瀚云, 吕珍珍, 宗美荣, 李博文, Ciftci Emin, Sener Mehmet Furkan. 土耳其棉花堡与中国黄龙和白水台钙华退化原因对比研究[J]. 中国岩溶, 2021, 40(6): 1069-1076.
DONG Faqin, DAI Qunwei, ZHAO Yulian, CHEN Mulan, RAO Hanyun, LV Zhenzhen, ZONG Meirong, LI Bowen, Ciftci Emin, Sener Mehmet Furkan. Comparative study on the causes of travertine degradation between Pamukkale in Turkey and Huanglong, Baishuitai in China[J]. Carsologica Sinica, 2021, 40(6): 1069-1076.

[69] Akbulutc G. Geotourism in Turkey[J]. GeoJournal Library, 2016, 121: 87-107.

[70] Doan U, Ylmaz M. Natural and induced sinkholes of the Obruk Plateau and Karapinar-Hotamis Plain, Turkey[J]. Journal of Asian Earth Sciences, 2011, 40(2): 496-508.

[71] Ozdemir A. Investigation of sinkholes spatial distribution using the weights of evidence method and GIS in the vicinity of Karapinar (Konya, Turkey)[J]. Geomorphology, 2015, 245: 40-50.

[72] 许百立. 土耳其水资源及其开发[J]. 水力发电, 1997(11): 51-54.

[73] 许燕, 施国庆. 土耳其水资源及其开发与利用[J]. 节水灌溉, 2009(12): 54-57.

[74] Karanjac J, Günay G. Development of karst water resources in Turkey with emphasis on groundwater[J]. Natural Resources Forum, 1980, 4(1): 61.

[75] Yücer A A. The land use in Turkey: A general assessment and affecting factors[J]. Journal of Geoscience and Environment Protection, 2020, 8(10): 102-116.

[76] Çolak A H, Rotherham I D. A review of the forest vegetation of Turkey: Its status past and present and its future conservation[J]. Biology and Environment, 2006, 106(3): 343-354.

[77] 崔俊艳, 李胜涛, 姚亚辉, 刘东林, 刘伟朋, 王君照. 土耳其地热能产业发展对中国的启示[J]. 中国地质, 2023, 50(5): 1375-1386.
CUI Junyan, LI Shengtao, YAO Yahui, LIU Donglin, LIU Weipeng, WANG Junzhao. Development of geothermal energy industry in Türkiye and its enlightenment to China[J]. Geology in China, 2023, 50(5): 1375-1386.

[78] Bilgin O. The importance of geothermal energy resources in Turkey[J]. Open Access Library Journal, 2018, 5(2): e4317.

[79] Mertoglu O, Simsek S, Basarir N. Geothermal energy use: Projections and country update for Turkey[C]//Proceedings of World Geothermal Congress, 2020.

[80] 吴林强, 张涛, 苗淼, 徐晶晶, 杨振, 蒋成竹, 梁前勇. 土耳其海洋油气勘探开发现状及合作潜力[J]. 地质通报, 2021, 40(2-3): 401-407.
WU Linqiang, ZHANG Tao, MIAO Miao, XU Jingjing, YANG Zhen, JIANG Chengzhu, LIANG Qianyong. Exploration and development status of offshore oil and gas resources in Turkey and its cooperation potential[J]. Geological Bulletin of China, 2021, 40(2-3): 401-407.

[81] 刘伟, 宋国明, 李延河. 土耳其矿产资源管理与投资前景分析[J]. 中国矿业, 2014, 23(10): 61-64.
LIU Wei, SONG Guoming, LI Yanhe. Mineral resource manage-

ment of Turkey and analysis of investment prospect[J]. China Mining Magazine, 2014, 23(10): 61-64.

[82] Jasper C. China's property slowdown rocks Turkish marble exports[J]. Bloombergcom, 2019.

Overview of karst geology in Turkey

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Abstract　Turkey is distributed with karst up to about 40% of its land area, in which karst is developed under typical Mediterranean climate. According to the structural characteristics, Turkey is divided into four different karst areas from north to south, among which the Taurus mountains is the largest and most developed karst area in this country and even in the Mediterranean region; therefore, karst in Turkey is of high research value. Based on the systematic collection of geological, structural and hydrogeological data, this study compiles a 1 ∶ 100,000,000 karst geological map of Turkey, analyzes the factors affecting karst development, and summarizes the distribution law of karst in Turkey, the main karst phenomena and the current situation of resource exploitation and utilization.

Many external and internal factors contribute to the type and the degree of karstification of carbonate rocks. However, the basic fact is that the geological structure, the orogeny, and the connected tectonics provide the basic framework that permits, enhances, or impedes the processes of karstification. The Alpineorogeny and the following epiorogenic movements in Turkey have become important factors in karstification. This type of karstification of carbonate rocks is distributed almost everywhere in Turkey.

According to the structural characteristics, karst areas in Turkey can be divided into four units: the karst area of the Taurus mountains, the karst area of southeast Anatolia, the karst area of central Anatolia, and the karst area of northwest Anatolia. The region of the Taurus mountains is the largest and most developed karst area in Turkey and even in the entire Mediterranean region. Carbonate rocks developed from the Cambrian to the Neogene are mainly distributed in Mesozoic and Cenozoic strata, and are the most developed in the Jurassic and Cretaceous strata. In some places, the total thickness of carbonate rocks is more than 1,500 m. The most notable karst geomorphic features are karst caves, sinkholes, dissolution funnels, poljes, karst depressions, karst canyons, karst springs, underground rivers or lakes and submarine springs. From the Mesozoic to the Holocene, limestone was deposited by thrust-nappe effect on the strata with extremely low permeability such as schist, sandstone, shale, etc. Numerous fractures generated by tectonic movements became water channels. Many large-scale karst springs composed of Mesozoic limestone, Tertiary limestone and conglomerate were developed on the contact surface between limestone and impermeable strata, which made the area home to the world's largest karst aquifer and karst hot springs.

Carbonate caves in Turkey are mainly concentrated in the Taurus mountains near the Mediterranean Sea, the central and western karst areas of the Black Sea, and the karst areas of Thrace. Although gypsum caves are developed in the central region of Anatolia, the number is limited and the scale is small. Due to differences in geological and climatic conditions, caves in the Mediterranean region and caves in the Black Sea region show different morphological characteristics.

(1) The karst area of Thrace is dominated by ancient karst, with single-layer horizontal caves at altitudes of 40–60 m and multi-layer horizontal caves at altitudes of 240–450 m.

(2) Dolomite and volcanic rocks are widely distributed in the karst area of the western Black Sea, in which karst is not developed vertically and multi-stage horizontal caves are mainly developed below the altitude of 350 m.

(3) Vertical caves are mainly developed in the karst area of central Black Sea, some of which are more than

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has, this module can display various information on geological data to users, and provide functions such as fuzzy retrieval, advanced retrieval, sorting, and data export. According to their needs, users can obtain data by selecting different attribute sorting, setting the numbers of pages and multi-attribute joint query conditions, etc. Through multi-attribute conditional joint query, the data query range can be narrowed down, and the query results can be accurately obtained, solving the problem of large data retrieval.

The directory query module can realize the retrieval of geological data based on the content input by users. This module decomposes the query statement input by users, queries word by word to improve the query accuracy, and facilitates users to obtain the required data. Based on the results of word segmentation query, users can further filter data by data category, scale, and administrative region, and the keywords searched are highlighted in the query results. Users can click on the title to enter the page for data details.

With the use of spatial information on geological data, the one map module for karst geological data can realize the map spatial retrieval of various geological data, based on spatial topology. Users can choose to query data categories and scales, and obtain data information through various methods such as inputting map sheet numbers, dragging boxes, and polygon queries. The map displays the location of the data, and the list on the right displays the name of the data. If users click on the spatial position of the data on the map or the name of the data in the query results list, the data information window will display for users to enter the page for data details.

The map service module can realize the online viewing and attribute query of professional map elements. Users can select the professional geological map layer to be queried according to their needs, switch between vector maps, remote sensing images, terrain, and other base maps, view the legend, adjust the layer transparency, and use point selection, line selection, and surface selection to query attribute information.

These modules use various ways to display the spatial, temporal, related attributes, and other metadata information of karst geological data to users, realizing the informationization of geological data management services and improving the efficiency of data query and access.

Key words karst geology, data query, shared services, open-source framework

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200-meter deep, but the deepest cave is less than 300 m, due to the thin limestone thickness.

(4) In the karst area of the Taurus mountains near the Mediterranean Sea, overthrust faults are developed, and the thicknesses of carbonate rocks in some areas are more than 1,000 m, in which vertical caves are mostly developed. Both the longest cave and the deepest one in Turkey are located in this karst area.

By the end of 2019, there were 52 caves in Turkey with a depth of more than 200 m, 43 of which were located in the karst area of the Taurus mountains near the Mediterranean Sea, and 7 in the karst area of central Black Sea. There were 62 caves with a length of more than 1,000 m, 34 of which were located in the karst area of the Taurus mountains near the Mediterranean Sea, 16 in the karst areas of central and western Black Sea and Thrace.

Turkey is rich in karst resources such as marble, geothermal, oil, natural gas, etc., and it has abundant karst landscapes including large springs, caves, canyons, and travertine. The potential for development and utilization is vast, and there is an urgent need to conduct detailed karst hydrogeological surveys.

Key words Turkey, karst geology, karst distribution, cave, karst spring

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