

[卢耀如 张凤娥 著]

硫酸盐岩岩溶及硫酸盐岩 与碳酸盐岩复合岩溶 ——发育机理与工程效应研究

卢耀如



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——发育机理与工程效应研究**

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内容简介

本书是作者长期研究硫酸盐岩(石膏等)岩溶及其与碳酸盐岩(石灰岩、白云岩等)复合岩溶的总结。本书将野外调查与实验探索相结合,将机理研究与工程实践相结合,将地质作用、化学作用与生物作用相结合,深入揭示有关岩溶作用的机理。作者以调查研究成果为主体,也融入了国外的有关情况与认识,归纳出了对硫酸盐岩岩溶与复合岩溶机理的认识,并总结了有关工程效应与灾害防治的途径与方法,具有很好的参考价值。

本书可供岩溶、水文地质、工程地质、环境地质、矿业、水利、电力、岩土工程、农业、建筑等方面的科技人员、教师、专家、工程师及大学高年级本科生、研究生参考。

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总 序

工程科学技术在推动人类文明的进步中一直起着发动机的作用,是经济发展和
社会进步的强大动力。自20世纪下半叶以来,工程科技以前所未有的速度和规模迅
速发展,其重要作用日益突显,并越来越受到人们的重视。

中国工程院是中国工程科技界的最高荣誉性、咨询性学术机构。中国工程院院
士是中国工程科技领域的最高荣誉性称号,授予对中国工程科技发展做出杰出贡献
的工程科技工作者。院士们充分发挥群体优势,围绕国家、产业和地方经济社会发
展迫切需要解决的重大科学技术问题,开展宏观性、战略性、前瞻性、综合性的咨
询研究,为国家决策提供支持。他们的研究代表中国在该领域中的最高学术水平。
院士们视发展工程科技、促进国家经济发展和社会进步为己任,勤奋工作在各自的
专业领域,为祖国的繁荣富强、为国家安全和国防建设做出了重要的贡献。院士的
学术著作,是院士多年刻苦钻研和辛勤劳动的成果,是他们智慧的结晶,也是整个
社会的宝贵财富。这些学术著作,不仅对我国工程科技工作有重要的指导作用,并
且具有极高的学习和参考价值,对于促进年轻工程科技人才成长,造就出类拔萃的
青年科学家和工程师,推动我国工程科技事业不断发展具有重要作用。

感谢高等教育出版社设立中国工程院学术著作出版基金,资助出版《中国工程
院院士文库》,把院士们的学术成果向全社会推广。此举不但有力地支持了我国优
秀科学技术著作的出版,也对促进我国科技事业发展、繁荣科技出版事业具有重大
意义。

徐匡迪

2005年8月

第一作者简介



卢耀如 岩溶及有关水文地质、工程地质、环境地质学家。1931年5月出生，福建福州人。1950年入清华大学地质系本科学习，1952年院校调整入新组建的北京地质学院（现为中国地质大学，北京）水文地质工程地质系。1953年于北京地质学院提前毕业。1997年当选为中国工程院院士。现为中国地质科学院研究员、博士生导师，同济大学兼职教授、博士生导师，领导教育部城市环境与可持续发展联合研究中心，为国家减灾委员会专家委员会委员及国家环境咨询委员会委员。

50多年来，他潜心研究岩溶地区的水文、工程与环境地质问题。参加实践及指导一系列水利水电工程的勘测研究，涉及长江、黄河、珠江、淮河等许多流域，包括三峡、乌江渡、新安江等百多座水利枢纽；指导有关交通、城镇、矿山等建设的工程与环境地质勘测研究；研究有关地质-生态环境，为岩溶地区开发作出了贡献；积极进行地质灾害防治工作，为重大灾害防治提出了重要的科学认识，作为决策的依据。20世纪60年代初主持了我国第一个岩溶研究室，倡议并首先筹备岩溶地质研究所。建立了一套有关岩溶发育与工程效应的理论。以在岩溶（喀斯特）研究上的卓越成就，被誉称为“喀斯特卢”。获得了有关地质-生态环境的新认识，首先提出岩漠化（石漠化）的概念，开拓了为经济发展而研究与探索的范围。曾任我援外大型工程的高级专家，并曾在欧美国家及港台地区讲学。已公开发表近百篇中英文论文和10部论著。其中，代表性论著有：《中国岩溶——景观·类型·规律》、《中国岩溶》、《中国岩溶（喀斯特）发育基本规律及其若干水文地质工程地质特征》、《中国南方（岩溶为主）地区地质-生态环境图系》、《岩溶水文地质环境演化与工程效应研究》、《地质-生态环境与可持续发展——中国西南及邻近岩溶地区发展途径》等。曾获全国科技大会奖、地质科技二等奖、全国科技图书二等奖及李四光地质科学荣誉奖。

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Lu Yaoru



Lu Yaoru, expert of karst and hydro - engineering and environmental geology, was born in 1931 in Fuzhou, Fujian Province. He studied at the Department of Geology of Tsinghua University in 1950, then turned to the Department of hydro-engineering geology of Beijing College of Geology in 1952, and graduated ahead of time in 1953. Now he is the Professor of Chinese Academy of Geological Sciences and part-time Professor of Tongji University etc. He also is the member of Expert Committee of the National Commission for Reduced Hazards, and the Member of the National Environmental Consultative Committee, and he leads the Joint Research Center of Urban Environment and Sustainable Development, Ministry of Education, People's Republic of China.

Professor Lu has researched the karst and related hydro-engineering and environmental geology for 53 years. He led and/or directed the researches and prospecting works of a series of water conservancy and water power constructions, which related to Yangtze River, Yellow River, Zhujiang River, Huaihe River etc. river systems, such as Sanxia (Three Gorges), Wujiangdu, Xin'an Jiang etc. projects; he has also directed the investigations and researches of communication, cities and towns etc. constructions; and he also made the contribution for the development of karst regions by studying the karst geo-ecology and for prevention and treatment of geo-hazards. He has found a set of theories related to karst developmental rules and engineering impacts. For his outstanding contributions on karst researches, he got the prized name "Karst Lu". His important works are: Karst in China—Landscapes · Types · Rules, Karst in China, Research on Evolutions of Karst Hydro-geological Environments and their Engineering Impacts, Geo-ecology and Sustainable Development—Developmental Ways for karst regions of Southwest China and Neighbor Regions etc Publications and a series of karst maps as well as about one hundred papers. He got the awards related to National Sciences Conference in 1978, Geological Sciences and National Excellent Scientific and Technological Publications, and he got the J. S. Lee Honors Prize for Geological Sciences in scientific Research 1999.

He was elected the Academician of the Chinese Academy of Engineering in 1997.

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第二作者简介



张凤娥 女，1964 年出生，山西省汾西县人。1986 年毕业于长春地质学院水文地质工程地质系水文地质专业，获工学学士学位；1992 年在中国地质科学院研究生部获理学硕士学位；2005 年获中国地质大学（北京）博士学位。现为中国地质科学院水文地质环境地质研究所研究员。

自参加工作以来一直从事水文地质、岩溶水文地质和环境地质方面的研究工作，近年来又开展了地下水微生物的应用研究。先后参加和主持了 20 多项重点研究项目，包括国家攻关、国家计委、973 项目、国家自然科学基金项目及中国地质调查局项目。目前更多地关注微生物和硫在岩溶研究中的应用。

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Zhang Feng'e



Dr. Zhang Feng'e was born on October 9, 1964, in Fenxi County, Shanxi Province. From 1982 to 1986, she studied in the Department of Hydrogeology and Engineering Geology, Changchun College of Geology and graduated with bachelor's degree. And then, she got her diploma (M. Sc.) in hydrogeology, Chinese Academy of Geological Sciences in 1992. From 2001 to 2005, she studied for Ph. D supervised by Professor Lu Yaoru and Professor Chen Honghan in China University of Geosciences, Beijing. Since 2005, she has been a professor of the Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences.

Her research interests involve in hydrogeology, karst and environmental geology. She has finished about twenty projects which were funded by the Ministry of Sciences and Technology, National Natural Science Foundation of China, China Geological Survey. Her current research interest is the role of microorganism and sulfur in karst development.

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序 言

碳酸盐岩（石灰岩、白云岩等）在我国分布广泛，发育的岩溶现象多种多样，构成许多著名的岩溶景观，不仅吸引了古今中外许多的旅游者，成为旅游胜地，而且也引起许多中外学者的关注。对碳酸盐岩岩溶的发育规律、机理，以及有关水文地质、工程地质及环境地质等方面的研究，已有很大的研究队伍，所取得的成果也是非常丰硕的。

硫酸盐岩（石膏、芒硝等）在中国也有较大面积的分布，与经济建设也有密切的关系。但是对中国硫酸盐岩岩溶的研究，与对碳酸盐岩岩溶的研究相比较，显然在研究力量、规模及成果等方面都显得不足。

石膏、芒硝等可直接为水所溶解，而且岩性软弱，在湿热气候条件下，大的硫酸盐岩岩溶现象多不易在地质环境变化较大的情况下得以长期保存。我国石膏等岩溶景观没有像碳酸盐岩中发育的石林、峰林及大型奇异洞穴那样得以长期保留。硫酸盐岩石膏等岩溶发育，有其独特的作用过程，而且硫酸盐岩又常与碳酸盐岩共生，因此深入研究硫酸盐岩岩溶的发育机理，进而研究硫酸盐岩和碳酸盐岩复合岩溶作用的机理，有助于深入认识与掌握碳酸盐岩岩溶发育的特征及其规律性，也是经济发展的需求。

相应的，在20世纪60年代初，我国对碳酸盐岩岩溶已开展调查研究之时，我们也进行了有关硫酸盐岩石膏岩溶的试验研究，以对比以石膏为代表的硫酸盐岩和以方解石、白云石为代表的碳酸盐岩之间溶蚀作用机理的差异性。

在相当长的一段时期内，我国对硫酸盐岩岩溶发育方面专门的理论探索较少，也没有系统的有关硫酸盐岩岩溶发育方面专门性的研究论著问世。在国外，有关硫酸盐岩石膏方面的专门论著也是少见的。

从20世纪60年代开始，我们注意到温度、水溶液性质对可溶性矿物（包括石膏）的溶解度的影响，从中探索了有关岩溶发育的机理。这是研究硫酸盐岩岩溶的早期阶段。后来，20世纪70—80年代，对硫酸盐岩岩溶的研究仍以这方面为主，但多从属于碳酸盐岩岩溶研究的一个内容。20世纪90年代，开始更多地注意到硫酸盐岩自身的岩溶发育机理，并密切地探索其诱发的环境效应问题，特别是1996—1997年，与英国地质调查局（British Geological Survey, BGS）Anthony H. Cooper博士开展了中英合作研究《石膏地质灾害：其发育与环境灾害》。这是硫酸盐岩岩溶研究的另一新阶段。

1996年 International Journal of Speleology (3~4期) 出版的题为 Gypsum

Karst of the World 的专辑, 其中包括了中英合作的部分成果; 另一合作成果《中国石膏岩溶地质灾害》出版在美国 1997 年召开的岩溶国际会议论文集中。

于 1999—2001 年, 得到国家自然科学基金的资助, 进行了《硫酸盐岩岩溶发育机理与环境演化效应研究》(编号: 49872095), 又对硫酸盐岩岩溶发育中的生物岩溶作用及其与碳酸盐岩复合岩溶问题作了进一步探索。

2006—2008 年, 国家自然科学基金资助的项目《碳酸—硫酸盐岩建造中复合岩溶发育的微生物作用机理研究》(编号: 40572144), 在微生物与复合岩溶发育机理方面又进行了深入研究。

目前, 进而探索硫酸盐岩与碳酸盐岩的复合岩溶作用机理, 使对复合可溶岩的岩溶发育机理研究更接近于自然界的实际情况, 也可更好地研究并解决有关环境效应和诱发的灾害问题。在复合岩溶研究中, 开展微生物岩溶作用的研究, 将自然界中存在的生物地球化学作用—物理作用—地质作用等进一步地结合, 以求更好地揭示硫酸盐岩和碳酸盐岩的复合岩溶发育机理与规律。

这本论著, 应当是 20 世纪 60 年代以来作者研究硫酸盐岩岩溶的总结。后来中英合作研究, 特别是国家自然科学基金的资助, 使对硫酸盐岩岩溶的研究得以深入提高, 进而开创了包括微生物岩溶作用在内的综合研究的新阶段。本论著中也包括了正在进行的国家自然科学基金项目《碳酸—硫酸盐岩建造中复合岩溶发育的微生物作用机理研究》(编号: 40572144) 取得的部分早期成果。

在此, 谨向国家自然科学基金委表示衷心的感谢! 感谢英国地质调查局的支持! 对中英合作研究中的英国首席科学家 Anthony H. Cooper 教授和 Dr. Tony Waltham 教授等表示诚挚的谢意。感谢 K. S. Johnson 教授, 由于他的帮助, 笔者在美国俄克拉何马州进行了相关的研究工作。在合作研究中, 得到王贵喜、张凤歧、葛文彬、韩至钧、马宏汉、姜德甫等专家的支持与合作, 也一并致谢。早期进行可溶岩溶解度探索性试验研究的有戴莺、贾温茹和戴杏娟, 近期参加有关溶蚀机理试验的有齐继祥、郭秀红、徐家明和刘广联等有关专家, 在此也一并致谢! 在开展有关生物岩溶作用方面, 得到阎葆瑞、张锡根、张胜和张云等专家的大力支持, 并参加这方面的试验研究, 使对硫酸盐岩微生物岩溶作用的研究取得进展, 在此表示衷心的感谢。在出版过程中, 得到贾秀敏、袁立娟、李翠、王娟娟和张静等的帮助, 特别表示衷心的感谢!

总之, 在硫酸盐岩岩溶发育机理及有关环境效应方面, 尚有很多的内容值得今后深入开展研究。希望本书的初步研究成果能够对今后的有关研究起到一些参考作用。

卢耀如

2006 年 12 月 1 日

SULPHATE ROCK KARST AND SULPHATE – CARBONATE ROCKS' COMPOUND KARST PREFACE

The sulphate rock included gypsum, anhydrite and mirabilite etc. is also widely distributed in China, and its karst is closely related to the economic constructions. To compare the studying works with the carbonate rock karst, it is obviously that the researches of the sulphate rock karst either in the contents or in the dimensions as well as the results in past times all are less and un-satisfied for the needs from constructions in China.

The different basic karst process between the soluble rocks is that the sulphate rock will be directly dissolved by the pure water solution, but the carbonate rock to be dissolved is mainly depended on the role of carbon dioxide in the $H_2O - CO_2$ system. Owing to the soft mechanical features and larger solubility in water, the sulphate rock such as the gypsum and anhydrite could not keep their special karst landscapes and shallow cave systems for long period under moist climatic conditions. Besides the development of sulphate karst with the different special karstification, the sulphate rock and carbonate rock are always deposited together, therefore to study the development of sulphate rock karst is the first step on research, then the compound karst related to sulphate rock and carbonate rock together as the important content must be paying more attention on the scientific purposes, which studying contents are also favourable for deeply understanding the fundamental rules related to karst development of carbonate rock.

In early 1960s, we have already studied the sulphate karst, and the special dissolution researches in laboratory have been taken, which tests used the gypsum, anhydrite, calcite and dolomite etc. standard minerals as the examples to measure their dissolution rates under different conditions to be controlled by the temperatures and water contents. For long times, we have mainly investigated the carbonate karst, but the sulphate rock karst is always involved together either in North China or in South China.

It is needed to emphasize that we have had the cooperative researches on "Gyp-

sum geo-hazard; development and impacts" with Dr. Anthony H. Cooper of the British Geological Survey (BGS) in 1996—1997, which results "Gypsum Karst in China" has been published in "Gypsum Karst of the World, International Journal of Speleology, Volume 25 (3-4), 1996" and "Gypsum Karst Geohazards in China" has included in the publication "The Engineering Geology and Hydrogeology of Karst Terraces, Proceedings of the Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Springfield/Missouri/6-9 April 1997".

From 1999—2001, we got the financial support from the National Natural Science Foundation of China (NNSFC) to study "Research on the Developmental Mechanism of Sulphate Rock and the Impacts of its Environmental Evolutions (No. 49872095)". A series of our papers have been published in Chinese and English Journals and other publications. A great deal of the studying results have, by many ways, discussed the karst development and related environmental problems in carbonate rock regions, which distributive area of bare and semi-bare conditions is over 1.3 million square kilometers in China. Therefore, this work is mainly reflected our researches on sulphate rock karst and sulphate-carbonate rocks' compound karst. In the past several years, we have done the special tests about bio-karstification, which results will provide the important data for studying the sulphate rock karst and sulphate-carbonate rocks' compound karst development. From 2006—2009, another studying "Research on the mechanism of microorganism roles related to the compound karst of carbonate-sulphate formations" (No. 40572144) is supported by the NNSFC, and parts of the new results are reflected in this work.

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out the important base for researching the bio-karstification involved to sulphate rock karst and sulphate-carbonate rocks' compound karst. This work still is a primary studying result for the complex problems related to sulphate karst and compound karst as well as the environmental impacts and geo-hazards. We hope that the work will have the role to cause more attention and cooperation in studying sulphate rock karst and sulphate-carbonate rocks' compound karst in China and over the World.

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Abstract

Chapter One General Situation Related to the Distributions of Sulphate Rock Karst

In first, it is mainly to introduce the distributions of gypsum and anhydrite in several important countries of the World, which are: 1. United States of America and Canada in North America; 2. United Kingdom, Spain, France, Germany, Italy, Ukraine, Russia etc. countries in Europe. Secondly, the general situations of the distribution of sulphate rock karst in China is introduced.

The sulphate rock belonged to the evaporate rock in China will be, based on the depositional environment and their lithological characters, separated into several kinds, which are: marine (evaporate) deposit facies; lacustrine (evaporate) deposit facies, hydrothermal deposit facies, volcanic deposit facies and secondary deposit facies etc. genetic types.

Based on the distributions of sulphate rock in China, its features will be summarized as follows:

1. The sulphate rock in China possesses of multi-genetic types, which lithological characteristics, depositional dimensions and distributions are different;
2. The sulphate rock in China is mainly included gypsum and anhydrite, which genetic types mostly are belonged to the marine (evaporate) deposit facies and inner lacustrine (evaporate) deposit facies;
3. The depositional sequences of sulphate rock have usually accompanied with the karst processes, therefore the early karst phenomena occurred in the depositional stages of sulphate rock will be remained as the fossil karst phenomena, and the mechanisms related to deposition and karstification were closely controlled by local palaeo-geological and palaeo-hydrological conditions;
4. The recent karst processes are still proceeding, and the developments of neo-karst usually are depending on the base of palaeo-karst to re-activity;
5. By the soft features of sulphate rock, the larger karst phenomena and caves