文章编号: 1008 - 2786 - (2011)6 - 721 - 08

国外土壤微形态学研究的进展

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摘 要: 土壤微形态学从 20 世纪 30 年代发展至今,取得了很大的进步,并广泛应用于土壤学各个领域,解决了很多土壤学问题。越来越多的学者应用土壤微形态学方法进行其他学科领域的研究,并取得了很好的结果。与国内比较,国外土壤微形态学各方面的发展都更早、更为成熟。从国外土壤微形态学的发展简况以及土壤微形态学在其他学科领域的应用研究最新进展进行报道,如土壤发生与分类、土壤肥力与土壤环境、考古与第四纪等,以期对国外土壤微形态学的研究成果做一初步的小结和为国内土壤微形态学的发展提供一定的参考借鉴。

关键词: 土壤微形态学;国外研究进展;应用研究
中图分类号: S152.2　　**文献标识码**: A

土壤微形态学从 1938 年 Kubiena 发表了"微土壤学"(Micropedology)正式创立开始至今已经有 70 多年的历史。与土壤学的其他分支学科相比尚属建立和发展很晚的学科了。同时因为我国引进土壤微形态学系在 20 世纪 60 年代,所以在我国土壤微形态学研究则更是起步甚晚的一新学科领域。目前国内也有一些相关报道,但研究成果仍显得薄弱和落后。由于土壤微形态学在很多研究领域都有其特殊的作用,因此其应用将越来越广泛。为了在我国更好地普及和应用,本文对土壤微形态学的发展,特别是国外研究的最新进展做一报道。

1 土壤微形态学发展简况

1.1 国外土壤微形态学的发端和简史

20 世纪 20 年代,奥地利土壤地理学家 Kubiena 将地质学的偏光显微镜技术和方法,引入土壤学研究,并在 1938 年发表了"微土壤学"(Micropedology)这部经典专著,以后又发表多篇有关著述,标志土壤微形态学的产生[1-3]。

20 世纪 60 年代,澳大利亚学者 Brewer 发表了"土壤垒结分析和矿物分析"这一部土壤微形态学的重要学术论著[4]。这部学术专著一发表,便得到许多土壤学者的重视,并在土壤学研究上广为应用。此后经过近十年的研究,Brewer 又对土壤微形态学的基本概念进行了修订和充实,这些研究在土壤微形态学的发展史上具有里程碑的意义[5]。

20 世纪 60 年代后,作为代表性的研究是前苏联土壤学者 Е. И. Парифенова 和 Е. А. Ярилова 所做出的贡献。1977 年她们出版了"土壤微形态研究指南"专著,该书在土壤基本垒结类型与土壤颗粒机械组成类型相结合的分类方法、粗细土壤颗粒的相关分布型式、土壤空隙的分类及与土壤孔隙壁物质的关系、土壤微结构型式、粘粒形成物分类、微形态计量等的鉴定和描述方面,提出了很多新的见解[6-8]。

20 世纪 80 年代中期,在当时的国际土壤学会事务局局长 Bullock 等策划下,5 位土壤微形态的资深学者编写了"土壤薄片记载手册"[9]。该手册强调和规范了土壤微形态的基本概念和术语,全面总

收稿日期(Received date):2011 - 04 - 11。
基金项目(Foundation item):中国科学院成都山地所前沿方向项目"中国土壤微形态研究"资助。[This work was supported by forward direction program of IMHE of CAS, "Soil micromorphology in China".]
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结了此前土壤微形态研究关于土壤薄片鉴定和描述的技术和方法，该专著的发表，必定在推动土壤微形态学更广泛的应用和国际交流上产生重要影响。

土壤微形态要素的鉴定是微形态研究的重点，微形态术语和鉴定体系的规范化尤其关键。进入到21世纪以后，代表著作是 G. Stoops 的《Guidelines for Analysis and Description of Soil and Regolith Thin Sections》这本土壤薄片描述手册的面世[10]，手册最后还提供了微形态要素的检索鉴定，解决了长期以来由于名词的繁多、术语的深奥及理解的不一致所造成的问题。这个时期由于计算机等技术引入到微形态学，微形态学得到了长足的发展，其基本概念及应用研究等方面都取得了较大的成果。

1.2 国际土壤微形态学的学术交流情况

国际土壤微形态大会是土壤微形态学科的盛会，从1962年在德国不伦瑞克召开第一次国际土壤微形态学大会开始，以后每四年在世界不同的国家举行一次，2008－09第13届国际土壤微形态大会在中国成都举行，这次会议极大的促进了中国土壤微形态学的发展[11]。

1984年国际土壤学会土壤形态专业委员会设立了库比纳奖，表彰那些为土壤微形态学发展做出突出贡献的科学家，是土壤微形态领域最高荣誉的奖项，目前已有9位科学家获得此项荣誉，按获奖时间的顺序分别是：E. Yarilova, R. Brewer, H. J Altemüller, G. Stoops, E. A FitzPatrick, L. Wilding, A. Jongerius, and Herman Mücher, Nicolas Fedoroff[12－15]。

此外，为了鼓励青年科学家从事土壤微形态学研究，从2008年起，还设立了微形态青年学者奖，用以表彰和鼓励在微形态领域做出优秀成果并已发表论文论著的青年学者，2008年授予了 Adrienne L. Ryan[16]和 Amy L. Brock[17]，2010授予了 Thilo N. H. Eickhorst[18－19]和 Shih－Hao Jien[20－21]。从2005年起，巴塞罗那大学、根特大学等世界著名高等学府每两年会举办为期两周的土壤微形态短期培训班，用以培养土壤微形态领域的后备人才。如：2009年，在巴塞罗那、加泰罗尼亚、根特就举办了土壤微形态短期培训[22－25]。

1.3 土壤微形态基本术语及方法研究进展

在土壤微形态学中，有6个经常被使用的和最重要的基本概念。即土壤基本成分、土壤粗粒质、细粒质、土壤垒结、土壤形成物和土壤微结构。土壤微形态在一些重要的基本概念、特征和类型鉴定描述等方面都还存在不同意见，因此在阅读土壤微形态文献以及在进行土壤微形态鉴定和描述时，都需要了解目前已广为应用的土壤微形态的鉴定描述系统。自土壤微形态学产生以来，出现了多种体系的描述术语，例如：Kubiena 出版的 Micropedology, Brewer 出版的 Fabric and Mineral Analysis of Soils，帕尔芬诺娃的《土壤微形态研究指南》，Jongerius 等出版的 Glossary of Soil Micromorphology, Bullock 等的 Handbook for Thin Soil Section Description 以及 Stoops 等出版的 Guidelines for Analysis and Description of Soil and Regolith Thin sections 等。其中，Bullock 等和 Stoops 的专著是土壤微形态研究领域中目前最有影响力的研究成果，其著作中倡导的土壤微形态分类和描述术语越来越多地被国内外学者所认同。

在土壤微形态研究中，土壤制片与显微镜技术装备是非常重要的两项技术，探索新的，更加适宜的制片技术以及提高显微倍数和分辨率便是土壤微形态两个重要的发展方向。现在普遍采用的环氧树脂－三乙醇胺低温固化－冷杉胶粘片法和冷杉胶－松节油低温渗胶固化－502胶粘片法，既能保持土壤原状，又具有制片简便易行等特点，为土壤微形态研究的普及提供了较好的技术保障。随着科技的发展，设计出来的多切盘自动切片技术，为土壤薄片的制备提供了一个快速简捷的方法，还避免了原来机器磨砂磨片导致的薄片污染[26]。另外，随着超微技术的发展，<30 μm 或更薄的土壤超微薄片的制备也已实现[27]。

随着高科技的发展，土壤微形态学的显微镜技术装备也得到了迅速的发展。如利用生物荧光标记结合荧光显微镜可研究土壤中微生物的形态、种类、数量、分布及变化等特征[28]。粒子束技术和计算机相结合产生的诸如扫描或透射电子显微镜、电子探针、X射线衍射仪、激光微探针光谱仪等分析设备，不仅能够在超微观尺度上观察土壤结构，而且能够对物质成分进行定量分析[29－30]。

随着计算机图像处理系统和3S技术的应用，使微形态的描述向数字化方向发展，从定性研究走向了定量研究和数值模拟，从二维图像向三维数字模拟发展[31－33]。近20年来，国内外在这方面的研究发展非常迅速[34－35]。

2　国外土壤微形态学在其他学科的应用研究进展

2.1　土壤发生与土壤分类

目前，土壤的理化性质，计算机技术，GIS，RS 以及土壤景观模型等技术和方法被广泛应用于土壤形成演化和土壤分类上[36]，其中应用土壤微形态学的理论和方法开展土壤形成和分类研究始终是重点领域。

2.1.1　土壤形成演化

土壤因环境不断变化，使成土过程变为复杂，在发生上具有一定的继承性和叠加性，而属多元发生型[37]。代表性的成果如：在伊朗，石膏干旱土是干旱土的主要类型。对三种不同地形（崩积扇，高原，冲积平原）的石膏干旱土的石膏，粘化，钙积层进行微形态研究，微形态特征结合土体构型，理化性质表明在不同地形上，石膏以不同的形成模式聚集，在崩积扇土壤中，同时存在石膏，黏化，钙积层，这表明在这一种地形上土壤的多元发生过程。根据微形态诊断特诊和诊断层，按照美国土壤系统分类修订版对石膏干旱土进行了亚类的分类[38]。运用微形态方法对印度河套平原中北部土壤进行发生学研究，发现他们中大部分土壤发生都属于多元发生。微形态证据是：耗减的淀积粘粒特别物质，钙质结砾岩，稳定厚实的淀积粘粒特别物质，风化的矿物[39]。

土壤形成的各种过程都受到不同成土因素或不同组合的支配，成土因素的组合错综复杂，成土过程随之变化无穷，从而发生形形色色不同的土壤类型。土壤形态学已被公认是研究诊断性土壤发生学必需的手段之一，通过提供土壤微形态资料可以帮助说明许多土壤形成过程[40]。国外在这方面的研究已经涵盖了从干旱区的土壤到热带湿润地区的土壤研究，包括风化作用，淋溶淀积作用，脱钙灰化，腐殖化等土壤发生过程[41-43]。田间结合室内微形态的方法对意大利南部卡拉布里亚区丘陵山区的 6 个土壤剖面进行土壤风化和成土过程的研究，结果显示原生矿物和母质对成土过程和风化过程具有很明显的影响。同时地貌，时间，气候也是很重要的影响因子[44]。伊朗伊斯法罕的富积石膏的土壤多分布在冲积扇、洪积平原以及山麓坡积平原。对土壤石膏层及其形成物研究其发生过程，微形态研究显示石膏层的形成进化序列经历了两个阶段[45]。美国爱达荷州帕卢斯地区的粘化干热软土常常具有焊接剖面，难以判别土壤发生与地层发生之间的关系。运用水文监测结合土壤微形态分析研究了该土壤的发生过程，其中微形态特征表明，裂隙中具有比较厚的淀积粘粒胶膜的粘化层主要是由第四纪全新世火山灰聚集形成，而同一土体的其他途径的粘化层明显要更老些[46]。对德国梅克伦堡州淋溶土进行系统微形态学研究，发现完整的粘粒胶膜和胶膜碎片相邻分布，这证明了粘粒的淀积作用是在全新世同时进行的[47]。对美国堪萨斯州中部丘陵的三种起源于黄土母质的粘淀半干润软土进行微形态研究，发现在土壤薄片中，随机分布着云母和蒙脱石矿物以及风化的黑云母，表明风化作用是矿物形成的一个重要过程[48]。巴西东南部高地最高处是典型的垂直带土壤发育序列，结合理化分析，矿物分析方法，阐叙了垂直带土壤发育序列的微形态特征[49]。

2.1.2　土壤系统分类

国际土壤分类正朝着定量化，标准化和国际化的方向发展，以诊断层、诊断特性为基础的美国土壤系统分类（ST 制）和国际土壤分类参比基础（WRB）代表了当前国制土壤分类的主流，当鉴别土壤类型发生困难时，土壤微形态学技术找出新的区分特征。每一土类，亚类以及其他土壤分类单元，特别是它们的各个发生层次都有其特定的微结构。从土壤微形态的薄片中可以看出这些现象。它不仅能作为鉴别土壤类型的指标，并可从新的角度阐明土壤的内在发生学本质[50]。美国、荷兰、加拿大、英国、澳大利亚等在定量土壤分类研究上是较有成果的国家[51-52]，应用微形态学方法进行土壤分类的代表性成果有：卢旺达西南高山的森林土壤发育于石英岩和云母砂岩，从土壤形态和微形态来看，属于灰化土壤。应用矿物学，化学分析手段结果表明只有微弱的无定形有机复合物的淀积作用，土壤的螯合淋溶过程跟生物活动，铁的风化关系不大。说明在这些灰化土壤中，螯合淋溶过程并不是灰化层和灰化物质形成的主控发生过程。提出在国际土壤分类体系中，灰化层和灰化物质的形成的定义应该优先选择土壤的形态和微形态特征，而不是土壤的化学属性[53]。对中国台湾东北部亚高山森林土壤的三个始成土进行研究，该始成土有一个薄层铁磐层。应用微形态方法对漂白层与薄层铁磐层之间的交界进行微形态研究，发现该薄层铁磐层的形成分为两个阶段，并用美国系统分类方法对其进行分类[54]。运

用形态学,微形态,理化性质分析方法对台湾东部海成阶地进行土壤年代序列的发生学研究，得出了不同发生历史的土壤的形态,微形态以及理化性质的变化. 并按照WRB和美国土壤系统分类进行土壤分类[55]。

2.2 土壤肥力与土壤环境

2.2.1 农业管理措施与土壤肥力

土壤微形态应用于土壤肥力方面的研究主要集中在研究各种农业管理措施对土壤肥力质量的影响[56-58],代表性研究如Kapur等通过研究地中海谷物轮作管理方式下土壤微结构的特征,分析了不同耕作管理制度下土壤物理性质的变化,为探索可持续的土地管理措施提供了理论依据[59]。

此外,土壤动物粪便的排泄物是反映土壤动物活动的有力依据,不少学者通过研究土壤动物排泄物的微形态特征,来研究不同的土壤管理措施对土壤肥力质量的影响。如:Davidson等通过微形态手段研究了土壤动物粪便形成物的形态及分布,从而研究高地草原土壤中土壤动物活动与土壤结构的关系,结果表明土壤动物的活动与土壤层次之间关系紧密[60-61]。Davidson等在苏格兰东南部高地施加石灰和未施加石灰的样地采集原状土样,应用微形态技术分析土壤中土壤动物粪便形成物和孔洞的情况,从而分析施加石灰措施对土壤动物活动的影响,为农业土壤的管理提供依据[62]。Sveistrup等研究了挪威东部三个不同土地利用和季节性冰冻样地的粉质土壤剖面的微形态和理化性质,从而分析其对土壤水和土壤颗粒的运移的影响,为研究土壤的演化方向以及如何进行土壤管理可以最大程度的减少土壤的水土流失等方面提供依据[63]。Adesodun等在苏格兰采集添加污水软泥和杀菌剂两种不同处理的草地原状土样,分析其土壤动物粪便形成物和孔洞的微形态特征,研究不同添加剂对土壤动物活动的影响[64]。

2.2.2 土壤生态与环境

近年来,土壤微形态一个重要的进展就是与环境科学的交叉应用。在分析土壤生态与环境问题上,土壤微形态具有自身的优势,如:Adamo等应用微形态以及SEM/WDS手段研究了意大利南部已被重金属污染的洪水对火山灰土壤重金属的影响,结果表明火山土壤中铬和铜是主要的污染元素,在土壤的表层和表下层的粉粘质胶膜里存在大量的铬和铜,这是由于富含金属的河流沉积物随着水分的移动沿着土壤空隙下移的结果[65-66]。Davidson等通过对苏格兰偏远农村地区的四个废弃耕地微量元素的测定研究了过去的施肥措施对土壤污染的累积,其中锌元素累积严重,应用微形态技术分析了其来源和累积的机制[67-68]。

2.3 考古和第四纪研究

2.3.1 考古学

国外应用土壤微形态进行考古的时间并不长,20世纪50年代,Cornwall首次利用古遗址中土壤微形态的特征重建了其环境变化的历史,进而解释了灰烬等人类活动遗迹的特征,成为将土壤微形态应用于考古领域的第一人[69]。同期,Dalrymple应用微形态技术分析古遗址的化石土壤及其他沉积物的微形态特征,明确文化层与腐殖层之间的关系,展示了土壤微形态分析在考古学研究中的作用[70]。到了1960、1970年代,土壤微形态分析在古器具如陶器等的结构研究中得到应用[71]。1980年代以来,学者在欧洲、中亚、中美洲等地的考古研究中做了许多土壤微形态分析工作,不仅推动了环境考古研究的深入,更为重要的是推动了《考古学中的土壤微形态分析》的出版。这本专著是在大量实践的基础上出版的,可以作为土壤微形态分析在考古学研究中应用手册,它标志着土壤微形态在考古学中应用的一个新阶段[72]。

在考古学研究中,土壤微形态分析主要在以下方面提供重要的信息:①进行环境考古研究,即分析区域环境演化与考古遗址形成及考古学文化发展的关系;②分析考古遗址内各类遗存的特征及其所反映的人类活动特点[73]。如:Karkanas等应用矿物学、化学沉积以及微形态技术对以色列的凯塞姆洞穴的旧石器时代文化层进行研究分析,研究结果证明凯塞姆洞穴是中更新世古人类习惯性用火的例子之一[74-75]。

2.3.2 古环境与第四纪研究

土壤微形态在第四纪研究中具有自身优势,从土壤的微形态特征可以了解从古成土条件到现代成土条件的变化以及土壤的发育历程。以土壤微形态学技术研究古土壤,进一步分析环境演化的进程已有很多报道[76-78],代表性研究有:McCarthy通过研究加拿大亚伯达省复杂的沉积物的微形态特征,重点研究了沉积物的粘土胶膜及铁质结核、侵染物的特征,从而分析了其形成的古环境条件[79]。Kuhn对德国梅克伦堡－前波莫瑞州淋溶土土壤剖面的微

形态特征进行了系统的研究,结果解释了圆形粘土胶膜碎片的发生机理,从而澄清了漂白淋溶土形成的古环境时间和条件[80]。两个长期更新世古土壤序列分别坐落在意大利北部的奥莱焦和马泽美瑞科,两个序列均可划分出6个成土单元,每个单元代表不同的成土过程。Kuhn等利用微形态方法对两个序列的的同一成土单元的微形态特征进行比较研究,取得了其他发生学办法无法取得的信息[81-82]。Srivastava等应用微形态研究喜马拉雅山脉西北冲积扇沉积物($10\sim50\times10^4$年)及邻近多元发生恒河平原土壤(主要是全新世)的发生学特征,研究结果可以表明晚第四纪发生的气候变化。结果显示,喜马拉雅山脉西北的古土壤的形成主要受末次冰期的暖期以及沿毗邻重点的移动控制。虽然气候波动以及腐殖酸-半干旱半湿润气候条件对恒河平原古土壤的形成起着主要的作用,但淀积作用、钙化、碳酸盐溶解等多元成土作用是该土壤的成土特征[83-84]。

3　土壤微形态学在其他学科研究领域的应用

经过70多年的发展,土壤微形态学从基本概念形成,研究层次结构和系统的完善,研究技术方法的改进,都取得了长足的进步,这些进展为土壤微形态在土壤学科及相关学科研究的应用打下了牢固的理论基础。

近年来,关于人为土的研究也越来越受到国内外土壤学家的关注。人为土可定义为在人类活动深刻影响下具有人为诊断层和诊断特征的土壤。人为作用的方式多种多样,除直接作用外,主要是通过影响和改变五大成土因素对土壤发生作用,这样就发生了更复杂的成土过程,有时候仅仅依靠一些剖面大形态特征以及一些基本理化分析很难对土壤进行分类,这时候土壤微形态学就能从另外一个角度找到突破口,解决其他方法所不能做到的系统分类问题。

此外,土壤微形态技术还被广泛的应用于土地退化(如土壤侵蚀和地力退化)、山地灾害(如滑坡和泥石流)、环境变化、材料化学等学科领域,学科的交叉研究也促进了土壤微形态学的发展和完善[85-90]。

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Review of Soil Micromorphology in Foreign

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Abstract: Soil micromorphology had made great progress since 1930s, and it is widely used in various fields of soil science to resolve plenty of problems. More and more scientists applied soil micromorphology in other disciplines, and had obtained convincible results. Compared with the domestic, developments of soil micromorphology in foreign were more matured. This paper summarized the latest progress of soil micromorphology and its applications in other disciplines, such as soil genesis and taxonomy, soil fertility and soil environment, archaeological and Quaternary, et al. This preliminary summary might provide some references for the domestic development of soil micromorphology.

Key words: soil micromorphology; foreign progress; application research

国外土壤微形态学研究的进展

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刊名： 山地学报 ISTIC PKU
英文刊名： Journal of Mountain Science
年，卷(期)： 2011,29(6)

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