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多年冻土过渡带研究进展与展望

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摘　要: 随着气候临界点的迫近,多年冻土两层分层体系的局限性日益凸显,因此有必要单独考虑多年冻土上部即过渡带的特殊性质.通过系统梳理已有研究发现:(1)过渡带是多年冻土区内成冰和过剩冰的主要分布带,广泛分布于粉黏土中及部分细粒多孔且冻结敏感性强的风化基岩地带,地下冰多为分凝冰、脉冰和大块冰,冷生构造主要为透镜状、层状、网状和斑杂状等,其变化与热融沉陷和斜坡地带热融滑塌、融冻泥流和活动层滑脱等现象密切相关;(2)其蕴含的丰富有机质和腐殖质常与多年冻土的加积和重复分凝成冰过程伴生,是重建冻土形成时气候与环境的可靠替代性指标;(3)多年冻土退化的程度和幅度与过渡带的厚度、冷生构造、地下冰和有机质含量等内在性质密不可分,呈现极强的时空异质性,其因地下冰巨大相变潜热效应而减缓甚至阻抗多年冻土退化,但一旦融化即产生临界点效应,由此多年冻土退化加速,热喀斯特现象激增,并造成上覆工程构筑物失稳.因此,亟待开展包含过渡带的气候环境重建、生态水文效应、力学性能和结构性质的演化与冻土精准模拟研究.

关键词: 多年冻土地下冰;过渡带;转换层;中间层;气候临界点;生态学;环境地质.

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Research Progress and Prospect of Transition Zone in Permafrost

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Abstract: As one of the critical climatic elements of the Earth system, the permafrost is approaching its climatic tipping point, highlighting the limitations of its two-layered structure consisting of active layer and perennially frozen layer. Therefore, it is necessary to consider the transition zone situated between the active layer and perennially frozen layer, which has specific properties, as a separate layer. The transition zone is the ice-rich upper part of permafrost, which thaws over sub-decadal to centennial time scales, particularly during extremely warm and wet summers, becoming part of the active layer. It comprises an ice-rich transient layer and an icier intermediate layer. The cryostructures, thermophysical properties, and mechanical structures of the transition zone are distinct from both overlying active layer and underlying permafrost, below which is the "authentic" permafrost. Under the combined influence of global climate warming and anthropogenic activities, the degree and extent of permafrost degradation are related to external forcing factors such as climate, environment, basic properties of watershed, and human activities, as well as internal properties like the thickness and position of the transition zone, cryogenic structures, ground

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ice, and organic matter content, displaying strong spatiotemporal heterogeneity. Research shows that transition zone is widely distributed in silty-clay and parts of frost-susceptible weathered bedrocks with fine-grained pores. It is the main distribution zone of intrasedimental ice and excess ice, with ground ice mainly existing as segregated ice, vein ice, and massive ice. The cryostructures are primarily lenticular, layered, reticular, and ataxitic, and their changes are closely related to phenomena such as thermal subsidence, thermokarst slumping, solifluctions, and active layer detachment. The rich organic matter and humus contained within are often associated with permafrost aggradation and repeated segregation ice formation processes, serving as reliable proxies for reconstructing the climate and environment of permafrost formation. Due to substantial latent heat effects of phase changes in ground ice, the transition zone can slow down or even resist permafrost degradation. However, once it melts, it triggers a tipping point effect, accelerating permafrost degradation, increasing thermokarst phenomena, and leading to the instability of overlying engineering structures. Therefore, it is urgent to carry out research on climate and environmental reconstruction, eco-hydrological effects, mechanical structure evolution, and precise permafrost modeling that includes the transition zone.

Key words: permafrost ground ice; transition zone; transient layer; intermediate layer; climate tipping point; ecology; environmental geology.

20世纪80年代以来,全球各地发生不同程度升温,其中高纬度增温速率为全球平均4倍以上,具有显著的北极放大效应(或称极地增温放大);而高海拔山地增温速率比全球平均也快1.5倍以上,被视为全球气候变暖的先兆区和启动区(IPCC, 2019;马丽娟等, 2022;Rantanen *et al.*, 2022).2023年成为过去2000年以来最热的一年,全球平均气温比工业化前(1980—1900年)高出(1.45±0.12)℃,进一步逼近《巴黎协定》设立的1.5 ℃控温目标(Esper *et al.*, 2024).多年冻土作为冰冻圈系统的重要组成成分,在快速增温和强烈人类活动叠加作用下,其对气候环境变迁的响应比其他组分更快,并已对全球气候和人类居住环境产生巨大影响,是地球气候系统16个临界要素之一(Steffen *et al.*, 2018; Lenton *et al.*, 2019; Armstrong McKay *et al.*, 2022;Liu *et al.*, 2023).然而,多年冻土对气候环境变迁的响应程度和幅度,及其变化对人类社会和上覆构筑物的影响程度,不仅受大气环流、水文地质、地形地貌、下垫面性质等外在条件制约,也在一定程度上与过渡带(*transition zone*)的厚度、冷生构造、地下冰和有机质含量等内在性质密切相关,具有很强的时空异性.

过渡带即富含冰的多年冻土上部,包括富含冰的转换层(*transient layer*)和含冰量更高的中间层(*intermediate layer*),其冷生构造、热物理性质和力学结构既不同于活动层,也与多年冻土有别.首先,过渡带是多年冻土地下冰最富集带,其孔隙被孔隙冰和分凝冰等所填充,比多年冻土其他层位具有更低的渗透性和更强的隔水效应,不仅造就多年冻土特有的冻结层上水/冻结层内水/冻结层下水水文结构(Cheng and Jin, 2013;Ma *et al.*, 2017;Luo *et al.*,2020),且因其巨大相变潜热效应而阻抗气候环境变迁.但多年冻土在极暖湿夏季的融化,又可能使局地和区域多年冻土水文循环产生拐点,如高温多年冻土被融穿导致地表水和冻结层上水渗漏(Luo *et al.*,2018a,2018b,2020),由此影响流域工农业生产、生活用水和生态安全(常启昕等, 2022; Pan *et al.*, 2022).其次,介于活动层当年底板与其长时段理论极值间的过渡带,是土壤冷生构造形成的主要场所之一,在多年冻土加积、沉积物堆积和重复分凝成冰过程中淤积了丰富的有机质和动植物残体,不仅保存了植被生长、土壤动物活动及生物地球化学循环等高寒生态的关键信息,还可提供多年冻土形成时的证据,对于理解全新世乃至晚更新世以来气候环境变迁和现今冻土形成具有重要科学意义(Shur *et al.*, 2005; Bockheim and Hinkel, 2010; Jin *et al.*, 2019).然而,冷生土壤及其气候环境指示研究多数集中于当年最大融化深度内,实际上并未深入到过渡带(Gubin and Lupachev, 2008).再次,过渡带是斜坡地带土(岩)沉积物在极暖湿夏季失稳的根源(Lewkowicz, 2007;Zwieback and Meyer, 2021),与融冻泥流、热融滑塌、活动层滑脱等现象密不可分(Lewkowicz and Harris, 2005a, 2005b;Luo *et al.*,2019,2022a,2022b;Mu *et al.*,2020),其融化会使工程构筑物失稳并可能造成重大经济损失和环境灾害(Niu *et al.*, 2016;Wu *et al.*, 2020;Hjort *et al.*, 2022),而致灾效应与其厚度、构造形态、地下冰含量及分布密切相关.

随着全球变暖导致多年冻土变化拐点的迫近,仅考虑活动层和多年冻土两层分层结构显然已无法满足科学和现实需要,有必要单独研究过渡带性质,厘清其冷生构造和地下冰的空间分布规律和基

本特征，揭示其对气候环境变迁的缓冲效应并量化其变化对生态环境和工程构筑物的影响．本文对过渡带的综述旨在加强对多年冻土加积或退化过程的认识，理解过渡带在气候临界点迫近时的气候环境意义，以提高多年冻土对全球变暖响应的预测精度及应对策略．

1　多年冻土的分层

1.1　相关概念

过去常将多年冻土从上至下分为活动层和多年冻土层（Bockheim and Hinkel，2010；French and Shur，2010；French，2018；Harris *et al*.，2018），其中，活动层是位于多年冻土层之上、夏季融化冬季冻结的浅地表层（Burn，1998；罗栋梁等，2023），而多年冻土是冻结状态持续两年或以上的土（岩）（周幼吾等，2000）．然而，这一分层体系容易忽略一些特殊情形．如，在多年冻土边缘地带存在一到两年内维持冻结状态的“隔年冻土”（*pereletok*）（Associate Committee on Geotechnical Research，1988；邱国庆等，1994），以及年变化深度低于多年冻土下限的活动“多年冻土”（Harris，2001），而极少数季节冻土区还存在深埋藏的残余多年冻土（Dobinski，2011）．又如，多年冻土的上限常因气候环境变迁而波动，使其上部在更长时段内经历冻融循环而成为活动层的一部分（Shur *et al*.，2005；Gubin and Lupachev，2008）．这一位于多年冻土上部的冷生土壤层，其地下冰含量比冻结期活动层与下伏多年冻土层都高，在几年到几百年时间尺度上融化，这一现象即为过渡带（Shur，1988；Shur *et al*.，2005）（图 1）．浅地表层内发生的冻融循环和水分物质迁移，形成了一系列标记融化前锋过去或当前位置的界线，造成地下冰空间分布及其属性的不连续，这便是融化不整合面（*thaw unconformity*）（French and Shur，2010；Lapalme *et al*.，2017）．过渡带下限为多年最大融化深度位置，可视为长期多年冻土上限（Bockheim and Hinkel，2010）．受多年冻土上部和活动层水热过程和物质交换的双重影响，过渡带的冷生结构、热物理性质和力学性能既不同于活动层，也与多年冻土有异．

参照包气带（*vadose zone*）和关键带（*critical zone*）等的翻译，笔者将 *transition zone* 表述为“过渡带”，而把构成过渡带的 *transient layer* 和 *intermediate layer* 分别译为“转换层”和“中间层”（Bockheim and Hinkel，2010）（图 1）．其中，转换层是在几年到几百年尺度上经历冻融循环的多年冻土上部，其厚度一般不超过活动层厚度的 30%（Shur，1988；Shur *et al*.，2005）．多年冻土在沉积物堆积、植被生长和气候变化等的作用下向活动层内加积，以及在由下向上的冻结冷吸和重复分凝成冰作用下形成新的多年冻土，便是中间层，其在十到百年尺度上受土壤气候和环境变化影响（Kanevskiy *et al*.，2011，2017）．由于风积物、崩积物和洪积物主要在地表沉积，而中间层处于活动层以下，因此中间层与多年冻土为准共生关系，即具备共生特征但实际无沉积发生，与下伏多年冻土有明显界限（Shur，

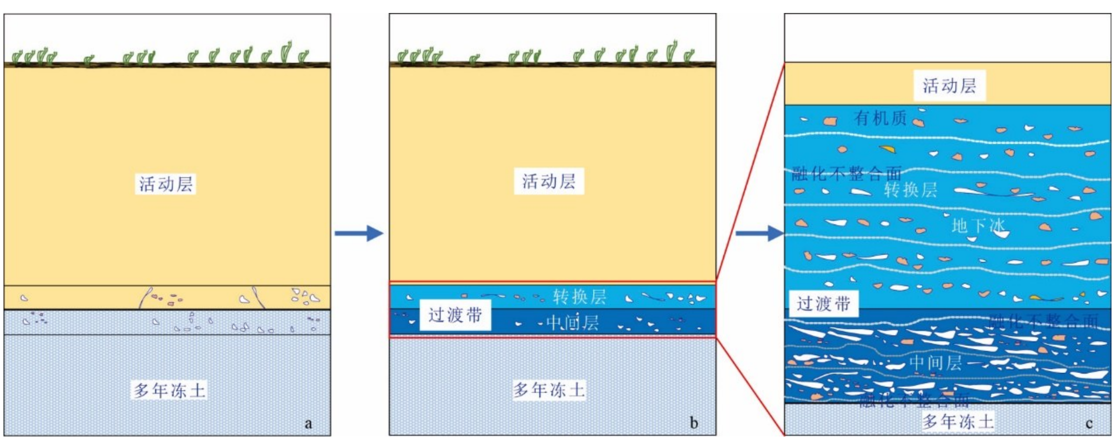

图 1　多年冻土分层体系

Fig. 1　Layered structure of permafrost

a. 活动层-多年冻土的两层概念模型；b. 活动层-过渡带-多年冻土的三层概念模型；c. 包含转换层和中间层的过渡带结构示意，白色不规则形状为地下冰，为由动植物和微生物残体组成的有机质，为悬浮状冷生构造，为包含垂直叶理脉冰的网状冷生构造，为层状冷生构造

1988).中间层以下为长达百年或千年处于冻结、不经历冻融循环的“真”多年冻土(French and Shur, 2010).中间层是地下冰最富集带,且富含有机质、细粒土以及泥炭,在粉质土含量高且富碳富冰的环北极冰楔复合体(叶叨码冻土)中十分发育(Kanevskiy *et al.*, 2013).过渡带因地下冰消长而变化,突出表现为增生地貌(泥炭丘、冻胀丘等丘状地貌,为正地形)和退化地貌(热融湖塘、热融洼地和冰楔坑等为负地形)的增减(Holloway *et al.*, 2017;Zwieback and Meyer, 2021).

1.2 发展阶段

早在1933年,苏联冻土学家Yanovsky在研究俄罗斯欧洲部分东北部多年冻土成土过程时就发现,多年冻土的上部在气候环境变迁下偶尔成为活动层的一部分,并用“过渡带”定义这一冷生土壤层(Yanovsky, 1933).根据这一发现,Sumgin *et al.*(1940)提出,若要获得真实的活动层厚度,应在当年测量值基础上适当予以增减.其变化量在强渗透性干燥土中可达1 m,而在有机质丰富的湿土中仅为0.1 m. Shur(1988)将该概念引进国际冻土学界,从形成过程、冷生构造及气候环境指示等方面加以阐述,并在美国自然科学基金支持下系统开展了研究(Shur, 1988;Shur *et al.*, 2005).

随着国际冻土协会(IPA)主导的环极地活动层观测计划(CALM)的成功实施,越来越多监测资料揭示了过渡带的基本特征.随后,过渡带的冷生构造、地下冰分布及其演化逐渐获得学界关注.当前研究多集中在阿拉斯加北部北冰洋沿岸、加拿大西北地区及西伯利亚等北半球高纬度多年冻土区(Shur *et al.*, 2005; Gubin and Lupachev, 2008; French and Shur, 2010; O'Neill and Burn, 2012; Kanevskiy *et al.*, 2013;Murton, 2013, 2022;Jorgenson *et al.*, 2015).我国学者近20年来高度关注活动层厚度的变化(Luo *et al.*, 2016),但很少将其与“过渡带”联系起来;仅在大兴安岭伊图里河发现不活动冰楔群时对过渡层(本文译为“过渡带”)的埋深、厚度和形成年代予以简单描述(杨思忠和金会军, 2010).虽然国际冻土协会(IPA)推荐的《多年冻土和地下冰辞典》(*Glossary of Permafrost and Related-Ground Ice Terms*)未收录这一术语,但在一些冻土学、冷生土壤学乃至地貌学专著中(Bockheim, 2015; Ballantyne, 2018; French, 2018; Harris *et al.*, 2018;Murton, 2022),均提及过渡带冷生构造、地下冰类型、分布规律及其影响因素,以及其气候环境指示作用.通过Web of Science检索与过渡带有关的发表于1993—2023年的学术论文,发现仅有100篇,总体引用也不高(图2).而且,迄今未有对过渡带的系统性认识,难以反映其在工程和气候环境叠加作用下的综合特征,因此有必要就过渡带的空间分布及其气候环境意义进行阐述.

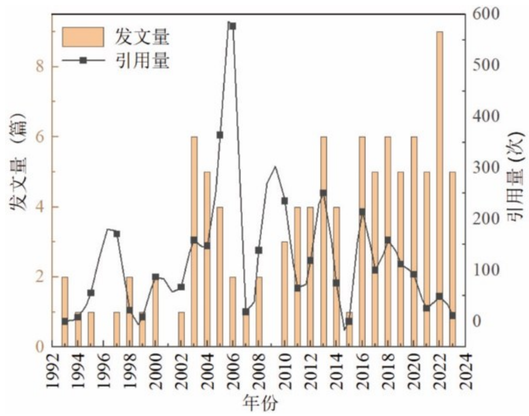

图2 基于Web of Science的1990—2023年多年冻土过渡带论文数量和被引次数

Fig. 2 Number of publications about transition zone and their citations related to permafrost from 1990 to 2023 retrieved from Web of Science

2 过渡带的基本特征

2.1 冷生构造和地下冰

2.1.1 土壤冷生构造 冻土中矿物质颗粒(骨架)和地下冰(冰晶、冰透镜体、脉冰、冰层等)的组合格局及形态特征为冷生构造,其与地下冰成因和类型,冷生扰动、冻融分选、冻胀和冻裂等过程密切相关,可通过地下冰、沉积物或岩石的形状、分布和比例进行辨识(Kanevskiy *et al.*, 2011;Murton, 2013; Gilbert *et al.*, 2016;Paul *et al.*, 2021).由于地形地貌、成土母质、赋存气候环境等土壤发生条件不同,土壤冷生构造形态各异(Kanevskiy *et al.*, 2011; Bockheim, 2015),大致可分为无结构(孔隙)、透镜状(微透镜状:<0.5 mm;透镜状:>0.5 mm)、层状、网状、不规则网状(编织状)、壳状、悬浮状(斑杂状)等构造(French and Shur, 2010; Kanevskiy *et al.*, 2011;Ping *et al.*, 2015;Paul *et al.*, 2021;Fan *et al.*, 2021)(图3).在富含地下冰特别是过剩冰的多年冻土区,一系列融化不整合可视为气候周期性波动的证据,其冷生构造形式相对多样化(French and

Shur, 2010; Paul *et al.*, 2021; Murton, 2022). 但和多年冻土、活动层不同的是，过渡带冷生构造的分布几乎与地面齐平，以层状、透镜状、斑杂状和网状为主（Murton, 2013, 2022; Ballantyne, 2018). 连续多年冻土区过渡带的冷生构造多为网状和斑杂状（Murton, 2013). 在无明显冻融扰动的情况下，过渡带冷生构造自上而下依次为网状、透镜状、层状和悬浮状，分别对应水分的原位冻结带、重分布带、分凝冻结带和冻结缘带（Kanevskiy *et al.*, 2013). 在部分冻结敏感性强的基岩地带，转换层由细粒土和完全风化的多孔泥灰岩、石灰岩及长石和页岩组成，有明显的层状、透镜状或网状冷生构造（Shur *et al.*, 2005). 中间层有的含垂直叶理脉冰，有的为土块悬浮于冰体的含土冰层，在北极叶叩码冻土分布区，位于过渡带以下的主冰楔，其顶部形成重复冰楔—地下冰呈悬浮状（或斑杂状、云雾状）和带状，总体呈现为透镜状、层状或带状（Murton, 2013; Ballantyne, 2018; Paul *et al.*, 2021). 而在少冰冻土区，过渡带冷生构造以层状和透镜状等为主.

2.1.2　地下冰特征及其成因　过渡带是多年冻土区内成冰和过剩冰最富集部位（程国栋, 1982; Kokelj and Burn, 2005; Shur *et al.*, 2005; Zwieback and Meyer, 2021). 地下冰的形成和演化是塑造冻胀丘、冻胀裂缝、热喀斯特、冰楔多边形等冰缘地貌的重要营力，同时也是过渡带形成、发育和变化的主因（Cheng, 1983; Burn and Michel, 1988; French and Shur, 2010; Kanevskiy *et al.*, 2013; Jorgenson *et al.*, 2015; Zou *et al.*, 2024). 不同于各种先形成于地表而后被沉积物掩埋的外成冰，过渡带地下冰为地壳中形成的内成冰，主要包括孔隙冰、分凝冰和大块冰（或称厚层地下冰）等，尤以分凝冰为最. 地下冰厚度则从 0.1～10 mm（微透镜体）到几十米（大块冰）不等（Murton and French, 1994; Kokelj and Burn, 2005; Paul *et al.*, 2021).

过渡带地下冰主要由多年冻土向活动层加积时的重复分凝成冰作用形成，或由气候较冷条件下的活动层变薄、或由沉积物及泥炭在地表的堆积形成，同时受大气降水、土体围压、水分供应量、土体冻结敏感性及其时长的影响（Mackay, 1995; Cheng, 1983; Burn and Michel, 1988; Ballantyne, 2018; Paul *et al.*, 2021). 过渡带内地下冰一般由水分的原位冻结和迁移冻结形成，不同冻结方式取决于冻结过程的水分补给量及冻结速率（Pollard and French, 1980; Kokelj and Burn, 2005; 徐敩祖等, 2010). 孔隙冰和胶结冰是冻土中常见的地下冰，由土壤孔隙或岩石裂隙中的水分冻结而成（周幼吾等, 2000)，一般不引起冻胀. 分凝冰是重力水和结合水在冷吸作用和温度梯度下向冻结锋面迁移而成，因地温梯度、冻结速率、饱水状态、粉土含量等形成条件差异而呈透镜状、层状或悬浮状等不同形状，共同指示着多年冻土的加积（Kokelj and Burn, 2005). 冻结速率过快或水分供应不足，难以产生或仅产生较

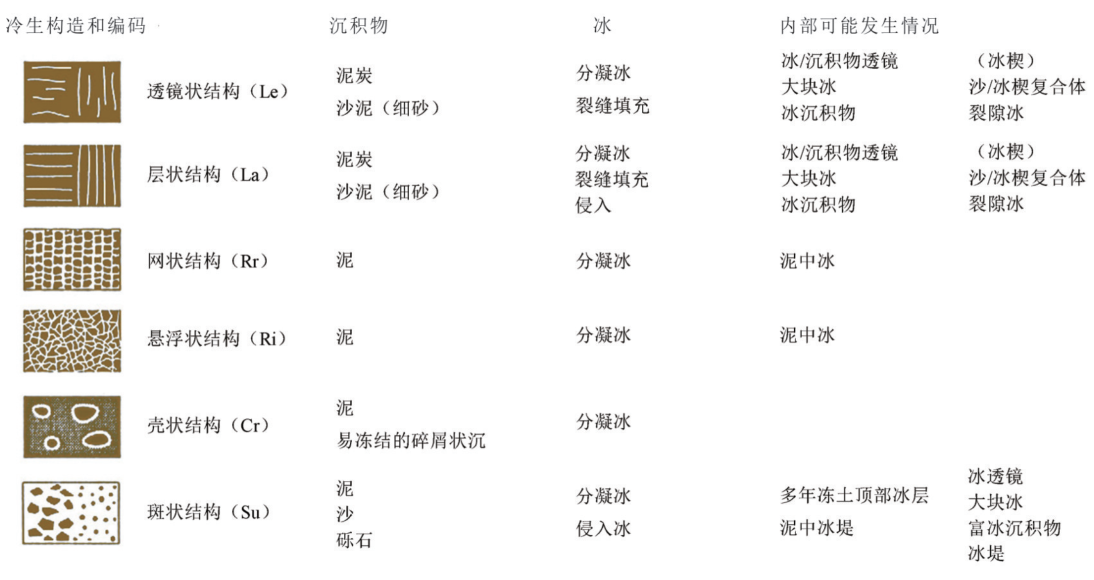

图 3　过渡带内主要冷生构造. 冰为白色，沉积物为棕色（修改自 Murton and French (1994))

Fig. 3　Main cryostructures and their codes within the transition zone. Ice and sediment are marked in white and brown, respectively (modified from Murton and French (1994))

少的分凝冰；而当地面较长时间维持负温状态时，冰透镜体或冰层就得以形成，驱动冻结缘向多年冻土迁移而形成过渡带（Ping *et al.*, 2015）. 冻结时间越长，则活动层冻结就越慢，冻结期向冻结锋面迁移的水分就越多，形成的地下冰也就越厚（Wu and Zhang, 2010；Luo *et al.*, 2014a）. 对细粒土而言，上限附近厚层地下冰形成的最佳年均地温（年变化深度（10～25 m）处地温）为－3～－5 °C（程国栋, 1982）. 具有粉质互层的沉积物有利于水分向冻结锋面迁移（Harris *et al.*, 2018），在侵入和重复分凝成冰作用下形成大块冰或厚层地下冰（程国栋, 1982）. 对非基岩类节理和裂隙而言，承压水由活动层底部回冻时贯入裂隙中并冻结形成侵入冰，其构成的静水压力将上部冻土层顶起，在地面上形成疱状冻胀丘（Harris *et al.*, 2018）. 冰楔冰在特定负温条件形成，一般认为其形成的年均地温不能低于－2～－4 ℃，且受围岩土壤质地影响，冻结敏感性强的细粒土形成冰楔的年均地温更低（Romanovsky, 1973）. 在冻土反复的冻胀、融化、劈裂等作用下，冰雪融水、融冻泥流、动植物和微生物残体等外源物质通过冻胀裂缝不断侵入并沉积到劈裂缝中.

中间层在长时间的水分原位冻结和迁移冻结共同作用下形成，与年复一年自下而上冻结、未冻水不等量迁移、冰的自净、沉积物加积等过程都有关，使其含冰率可达100%以上（程国栋, 1982；Shur, 1988）. 其地下冰由胶结分凝和重复分凝成冰作用而成，多呈带状透镜冰层，少部分由矿物质沉积而呈斑杂状的含土冰层（Shur, 1988）. 其形成过程可分为两个阶段：沉积阶段，正冻土并不形成中间层，季节融化层与多年冻土层间为转换层；随时间的推移沉积减缓直至彻底结束，多年冻土上部结构变得复杂并最终形成中间层. 中间层最显著的特征为地下冰与土壤呈水平互层分布，相对均匀，而下伏多年冻土的土壤结构和性质呈不均匀状态（Shur, 1988）.

2.2 空间分布规律

大量钻孔钻探和地球物理勘探表明，地下冰富集于浅地表10 m以内尤其是上限附近1～2 m深度的过渡带内，该深度也是气候变暖驱动下地下冰融化固结的应变敏感区（Jin *et al.*, 2008；赵林等, 2010；Kanevskiy *et al.*, 2013；Gilbert *et al.*, 2016；Bernard-Grand'Maison and Pollard, 2018；Wang *et al.*, 2018a, 2018b, 2018c；Castagner *et al.*, 2023；Lacelle *et al.*, 2022；Zou *et al.*, 2024）. 依据重要性排序，过渡带地下冰的形成因素依次为未冻水供应量、土壤沉积物的沉积速率及冻结敏感性、活动层冻融历史、地温梯度、水力传导系数、气相沉积和升华，特别是浅地表由下向上冻结过程中的水分不等量和季节性迁移容易形成重复分凝冰（程国栋, 1981, 1982, 1984；Mackay, 1995；程国栋等, 2019；Murton, 2022）. 大多数情况下，过渡带的形成、发育和演化与富含冰多年冻土加积过程和发展方向密切相关，且取决于沉积速率及土体冻结敏感性、多年冻土热稳定性及冻融循环历史、植被生长和冻结过程中的水分供应等（O'Neill and and Burn, 2012；O'Neill *et al.*, 2019；Kanevskiy *et al.*, 2013；Gilbert *et al.*, 2016；Couture and Pollard, 2017；Saito *et al.*, 2020；Lacelle *et al.*, 2022）. 总体而言，影响地下冰空间分异的因素既有地带性（陆-气间能量平衡、地温梯度、年均地温等热物理因素，降水等水文条件），也有非地带性（植被、冰缘地貌、地形特征，水文地质等）（Shur *et al.*, 2005；赵林等, 2010；Kanevskiy *et al.*, 2011, 2013, 2014, 2017；程国栋等, 2019；Zwieback and Meyer, 2021；Murton, 2022；Zhang *et al.*, 2023；Zou *et al.*, 2024）（图4）.

研究表明，过渡带在冻结敏感性强的粉黏土沉积物及部分完全风化的多孔细粒基岩中相对较发育（French and Shur, 2010；Murton, 2013；Ballantyne, 2018）. 因此，多年冻土年均地温越低，粉黏土含量越高，过渡带也就越发育. 从全球范围来看，西伯利亚中部及阿拉斯加山脉以北的北极低地广泛分布叶叨码冻土（图5b），以粉黏土沉积物为主，其分布面积达100多万 km^2，多年冻土厚达50 m以上，通常由埋藏中间层和埋藏泥炭相共生，受极低温、缓慢风成作用及晚更新世至全新世的气候环境变化影响形成（Kotler and Burn, 2000；Kanevskiy *et al.*, 2011；Gilbert *et al.*, 2016；Strauss *et al.*, 2021）. 此外，高北极部分岛屿，哈德逊湾南部的广大泥炭地，北冰洋沿岸马更些河、育空河等大河流域低地河谷地带，以及高山多年冻土区细颗粒沉积物丰富的垫状草甸山间盆地（Kanevskiy *et al.*, 2011, 2013；Jones *et al.*, 2019；Karjalainen *et al.*, 2023），过渡带可能相对较发育. 然而，占全球多年冻土66.5%的山地和高原多年冻土（Zhang *et al.*, 2008），加拿大北极群岛及格陵兰岛西部（Karjalainen *et al.*, 2023），地下冰含量相对较低，过渡带可能发育较弱.

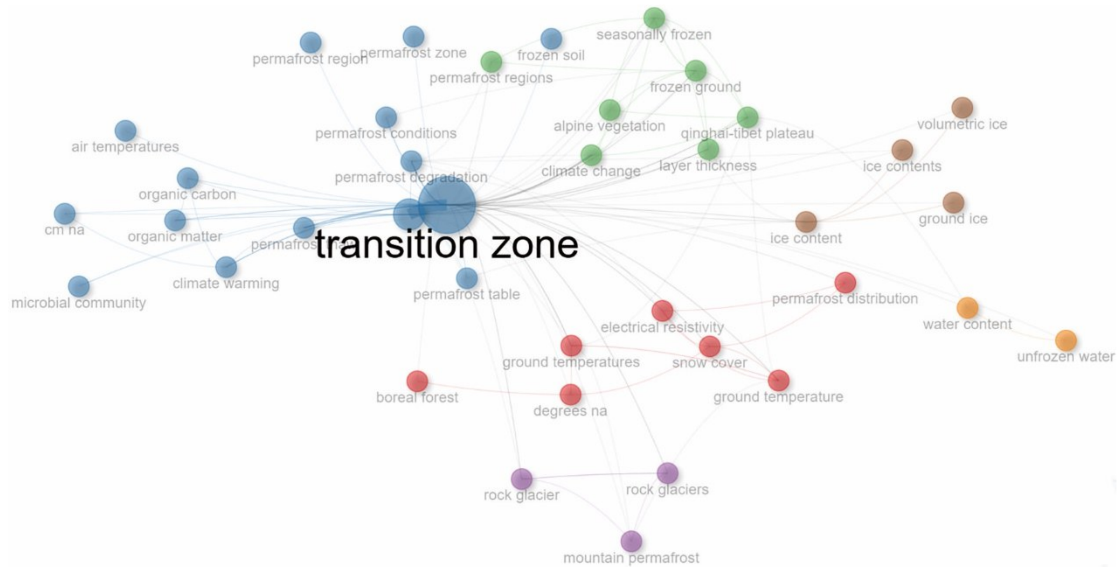

图 4　多年冻土过渡带关键词的共现图谱

Fig. 4　Co-occurrence network of keywords about transition zone related to permafrost

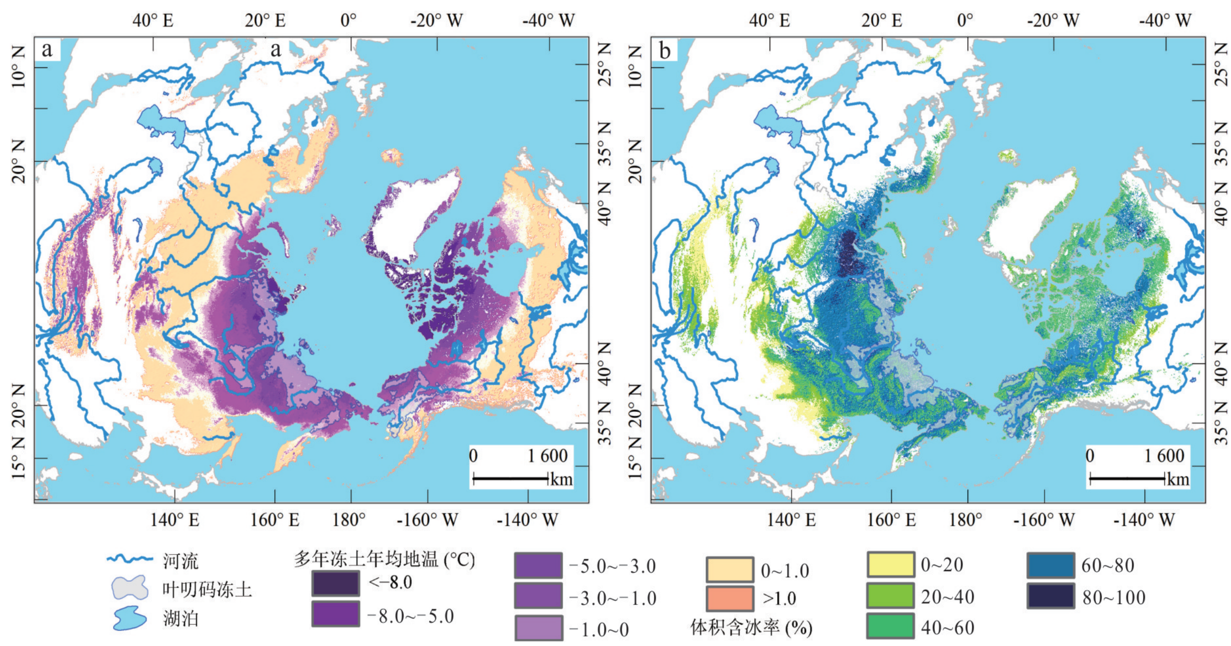

图 5　北半球多年冻土年均地温(地温年变化深度 10～25 m 处)(a)和多年冻土上限附近(主要为地表以下 5 m 内)体积含冰率空间分布(b)

Fig. 5　Spatial distribution of the temperature at the depth of zero annual amplitude (TZAA, 10–25 m) and volumetric ice content (VIC, %)

叶叨码冻土分布源自(Strauss *et al.*, 2021),年均地温源自(Ran *et al.*, 2022),地下冰体积含冰率源自(Karjalainen *et al.*, 2023)

2.3　过渡带研究方法

2.3.1　过渡带的确定　在实际工作中,常通过坑探剖面、钻探编录、热融滑塌壁等分析过渡带层位和厚度、地下冰含量及冷生构造(Williams, 1968;Kanevskiy *et al.*, 2011, 2013). 如, Bockheim and Hinkel (2010)利用阿拉斯加巴罗北冰洋沿岸平原 138 个土样,识别了 78% 的过渡带顶部和 70% 的底部. 过渡带底部可通过主冰楔顶部、过剩冰或冷生构造层理的突变来识别,一系列融化不整合面标志了过渡带的位置及活动层变化对气候环境的影响(Kokelj *et al.*, 2002;Bonnaventure and Lamoureux, 2013;Paquette *et al.*, 2020). 在冰楔分布区,过渡带

层位较好辨识,主冰楔顶部即为其底部位置,活动层底板至主冰楔顶部的距离即为过渡带厚度;在主冰楔上生长的二级冰楔顶底位置即为中间层顶底位置,而在二级冰楔顶部生长的三级冰楔为转换层顶底(Shur *et al.*, 2005;Kanevskiy *et al.*, 2011).如在我国大兴安岭伊图里河发现的不活动冰楔,多年冻土上限为0.6 m,冰楔顶部埋深0.9 m,过渡带厚0.3 m(杨思忠和金会军, 2010).当不存在冰楔时,转换层底部可由过剩冰及具明显垂直叶理的冰脉和网状冷生构造出现的层位辨识,而中间层地下冰含量更高、冰层更厚,且斑杂状冷生构造趋多(Kanevskiy *et al.*, 2011).

地表植被结构、沉积物类型、地下冰和冷生构造、土壤含水率等均与过渡带相关,因此常需结合局地条件以确定过渡带.植被茂密且覆盖度高的场地,其浅地表湿度大,地下冰含量也高.在加拿大理查兹岛的研究表明,表征过渡带发育的过剩冰在灌丛湿地的上限50 cm以内富集,而在干旱草地及植被稀疏地方其含量较低(O'Neill and Burn, 2012).在黑白云杉和白桦林场地,多年冻土上部富含透镜状和斑杂状冷生构造的地下冰,表明其存在中间层(Paul *et al.*, 2021).Mackay(1995)发现,在火后的森林和森林—苔原场地植被重生后,其下甚至会形成加积冰.未冻水供应和土体冻结敏感性是过渡带垂直结构、空间分布及其演化模式分异的关键,而地形地貌影响未冻水供应、排水条件、沉积类型和过程,这些因素的作用通常具有复合性.如:南坡第四纪松散沉积物一般较薄,岩性多残坡积碎石亚砂土和亚黏土,碎石含量较高,不利于地下冰发育,少厚层地下冰,体积含冰率一般为10%~15%,过渡带薄(Kanevskiy *et al.*, 2011);北坡松散沉积物发育程度虽不及谷底和洼地,但植被覆盖一般比南坡更好,过渡带地下冰含量介于谷底、洼地与南坡之间,体积含冰率为20%~35%(周幼吾等, 2000).而与场地含水量相比,场地位置的重要性居次.

2.3.2 过渡带空间分布的确定 过渡带与气候环境关系的量化是计算和模拟其空间分布的基础.上述分析表明,土体冻结时长和敏感性是地下冰发育过程、存在状态及其对气候变化响应程度的决定因素(Murton, 2013).而冻结时长与年均地温(年变化深度(10~25 m)地温)存在正相关性(程国栋, 1984):多年冻土地温越低,土壤冻结持续时间就越长,也就越有利于地下冰的长期形成和累积(Kokelj and Burn, 2005;Zhang *et al.*, 2008).因此,随纬度升高,多年冻土地温越低,过渡带的发育条件越好.此外,冰缘地貌是冰冻圈内水文地质、气候变迁、物理风化和生物地球化学过程等多种内外营力共同作用的结果,反映了土体的冻结程度和敏感性,而土体冻结敏感性也是地下冰分布的关键因素之一(Lacelle *et al.*, 2022).因此,冰缘地貌是过渡带局地分异的决定因素之一.富含冰多年冻土通过冻胀丘、活动层滑脱、溯源热融滑塌、冰楔多边形等冰缘地貌的野外调查和遥感反演可辨识过渡带(O'Neill *et al.*, 2019;Halla *et al.*, 2021;Lacelle *et al.*, 2022).过渡带厚度响应气候和土壤环境变化,通常不超过活动层厚度的30%(Shur *et al.*, 2005),与沉积物类型、厚度及其冻结敏感性有关.其在干燥的及粗砂、砾石或花岗岩等不易冻结土体中可能缺失,在活动层加深和融化过程中变薄,且由于大量过剩冰的积累需较长时间,因此在较晚形成的多年冻土中只有部分形成过渡带(Murton, 2022).

理论上,过渡带为一段时间内最大与最小活动层厚度的差值,因此活动层厚度对于确定转换层和中间层厚度十分关键.而活动层厚度本身可通过大气和地面融化指数、融土导热系数及冻土相变潜热等计算(Wu and Zhang, 2010;Luo *et al.*, 2014b, 2016, 2018b;Wang *et al.*, 2018).因此,在掌握地下冰及活动层厚度空间分布的基础上,基于降水、地形湿度指数、沉积物类型、土壤水化学、地温年均值及振幅、冰缘地貌及其成因和地表覆被的空间统计关系,结合遥感技术、模型模拟和机器学习,理论上可获得过渡带的空间分布(赵林等, 2010;Wang *et al.*, 2018a, 2018b, 2018c;Lin *et al.*, 2020;Lacelle *et al.*, 2022;Zhang *et al.*, 2023).转换层厚度可通过活动层厚度20~30年的平均值与多年平均值的差值计算,一般情况下为多年平均值的10%~15%,最多可达30%,而中间层厚度平均为1 m,最大可至2.5 m(Shur, 1988).过渡带的变化量与活动层厚度正相关,然而,过渡带的变化率却与活动层厚度呈负相关,且活动层厚度越小,过渡带与活动层厚度的比值就越大(Bockheim and Hinkel, 2010).比较研究发现,中纬度高山多年冻土活动层的厚度和变化量比高纬度的大,如阿尔卑斯山脉阿尔卑斯山脉和青藏高原活动层厚度变化率分别为5.2 $cm \cdot a^{-1}$和1.95 $cm \cdot a^{-1}$,而阿拉斯加和加拿大的仅为0.47 $cm \cdot a^{-1}$和

0.23 cm•a^{-1}(Luo *et al.*, 2016；罗栋梁等, 2023)，因此青藏高原多年冻土过渡带的相对变化量可能更大．需要注意的是，由于活动层厚度受土壤热物理性质(冻融导热系数比值、土壤粒径和含水率)的影响，比如，细粒土含量高的泥炭地，活动层厚度年际变化大于矿物质(Shur, 1988)．因此，当外界气温较高时并不意味着活动层厚度也一定大．在同一地区，有机质对活动层厚度的影响比矿物质大(Hollesen *et al.*, 2011)，因而过渡带变化量可能受外界气温、土壤质地等的复合影响．此外，活动层增厚和冻土融化可能会消除过渡带(Paul *et al.*, 2021)．

3　研究展望

冻土作为地球系统16个气候临界要素之一，其特征及演化对地球系统功能发挥与人类福祉具有重要影响(Lenton *et al.*, 2008, 2019; Steffen *et al.*, 2018; Armstrong McKay *et al.*, 2022)．冻土变化对地球系统影响的程度和幅度取决于其退化的过程、速率和模式．在对气候临界要素的认识中，Armstrong McKay *et al.*(2022)根据冻土退化特征将其分为3类，即渐进式融化(无阈值反馈，增温小于1.1～1.2 ℃)、突然融化(区域性临界要素，增温1.5 ℃(1.0～2.3 ℃))和坍塌(全球性核心临界要素，增温4 ℃(3～6 ℃))．冻土的突然融化和坍塌表现为冻土地貌景观的干扰和破坏，如热融洼地和湖塘、溯源热融滑塌、热融冲沟等负地形的突然和大量涌现，以及冻融草丘、冻胀丘等正地形的突然坍缩，这些均与过渡带对气候环境变化的响应特征和模式密切相关．大致而言，过渡带具有三方面的特性：① 丰富的可指示古(今)冻土形成气候与环境的替代性指标；② 巨大相变潜热效应；③ 特有的结构属性和力学性能(图6)．笔者认为多年冻土过渡带未来可展开以下研究．

3.1　过渡带的形成机制及分布制图

过渡带广泛存在于冻结敏感性强的富冰土岩中，其冷生构造、地下冰含量和性质与多年冻土和活动层均不同(Murton, 2022)．地下冰氢氧同位素是识别融化不整合面和活动层底部随气候环境变迁的重要证据(Murton and French, 1994)，并可用于鉴别过去活动层位置，以及全新世以来树线等气候环境指标的变化(Burn, 1997)．然而，过渡带形成后仍有水分在冷吸作用下向冻结锋面迁移并逐渐形成侵入冰，加之冻融扰动和搅拌，使元素含量发生改变，因此地球化学同位素并不总能有效鉴定融化不整合面和过渡带的厚度和位置，还需结合植物学、土壤分层等相关理论和证据．土壤分层理论认为，对于近乎平行地表的过渡带，其中的冰卷泥和冻融扰动等冷生土壤比其母体形成年龄更轻(Ballantyne, 2018)．

多年冻土区脆弱生态环境的修复和构筑物的安全运维，取决于对过渡带结构和性质空间分布的掌握．过去在多年冻土地下冰的半球或区域尺度分

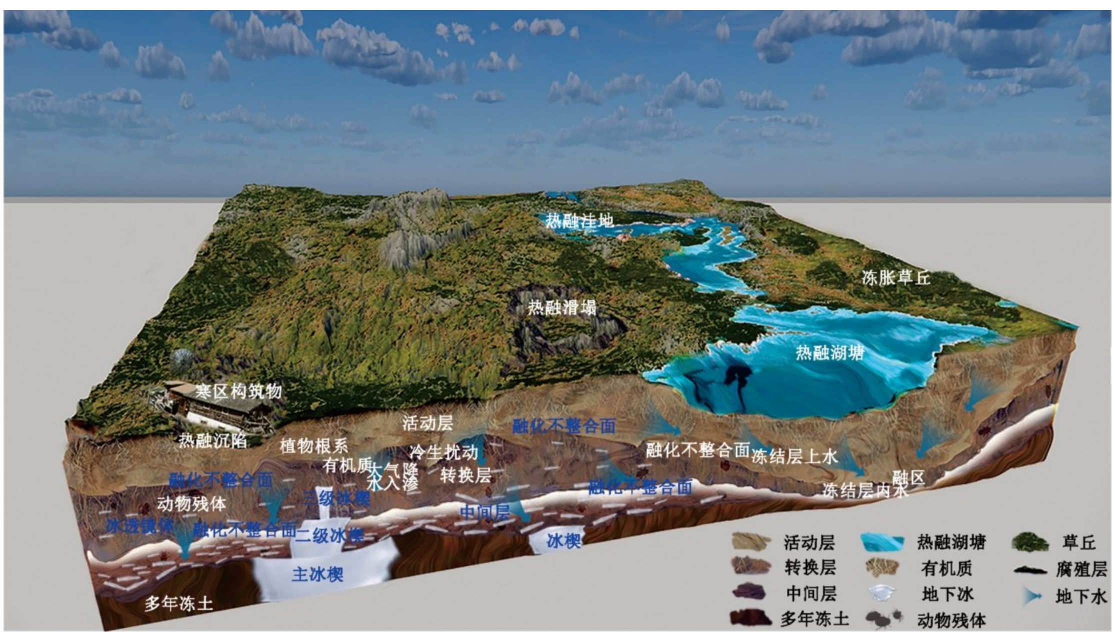

图6　多年冻土过渡带的冷生构造、地貌景观、地下冰分布及其灾害效应

Fig. 6　Schematic map showing cryostructure, land-scape, ground ice, and geohazard effects of the transition zone in permafrost

布制图方面已取得不少进展，为过渡带空间分布指标选取提供了借鉴.在研究过渡带空间分布时，可考虑冰川作用历史和现代多年冻土分布（O'Neill *et al.*, 2019），地表覆被特征（Dredge *et al.*, 1999），冻土模型以至陆面过程模型（Wang *et al.*, 2020；Saito *et al.*, 2021），以及冻土地貌.特别是指示了富冰冻土，尤其是大块冰存在的丘状地貌（Couture and Pollard, 2017；Kokelj *et al.*, 2017；Karjalainen *et al.*, 2020）.过渡带与土体的冻结敏感性高度相关，当前研究已发现过渡带在细粒含量高的粉质黏土沉积物中较为发育（Andersland and Ladanyi, 2003；Kanevskiy *et al.*, 2011；Ballantyne, 2018）.Karjalainen *et al.*（2023）在进行北半球地下冰空间分布制图时，由于缺少地下冰体积含冰率和土壤干密度信息，提出根据土壤质地确定多年冻土地下冰含量的转换系数，该系数在矿物质土壤中为2.5，矿物质土和泥炭混合物中为2.0，而泥炭中为1.5.因此，可结合地表覆被特征、土岩冻结敏感性、地形地貌、冻土过程等进行过渡带结构和空间分布的制图.

3.2 过渡带物源性质及气候环境指示

过渡带内一系列或平整或弯曲的融化不整合面本身即是气候环境变迁的印证.随着地质过程及冻融搅动的发生，过渡带内常常保存了含有过去环境变化信息的沉积物，包括草本、木本植物甚至是土壤微生物和动物残体等有机物质（Burn, 1997；Bockheim and Hinkel, 2010；Kanevskiy *et al.*, 2014；Murton *et al.*, 2015），并记录了冻土形成和演化的气候环境信息，因此通过替代性指标可反演古冻土和古环境（杨思忠和金会军，2010；Murton *et al.*, 2015）（图6）.即便地下冰因气候变暖而消融，也可通过过渡带内遗存的冰楔假型、冰卷泥和角砾状基岩等结构揭示过去冷生构造和反演古冻土分布（程捷等，2006；Zhao *et al.*, 2014；Jin *et al.*, 2020；He *et al.*, 2023）.此外，大气降水、地表水与冻结层上水的向下渗透迁移是过渡带地下冰形成的重要物质来源，通过对过渡带内地下冰同位素的分析，可获取自然和人类社会活动的高分辨率气候环境变化信息，如冷暖和干湿气候变迁、火山爆发及沉积、热核弹试验等（程国栋，1982；Burn and Michel, 1988；Wang *et al.*, 2018a, 2018b, 2018c）.比如，加拿大育空地区的一项研究表明，当代活动层以下0.5 m深度地下冰^{3}H含量急剧升高，反映出20世纪50年代热核聚变试验信息，是大气降水向下渗透迁移到多年冻土的结果（Burn and Michel, 1988）.

3.3 过渡带对多年冻土热稳定性的影响

因地下冰的巨大相变潜热效应，过渡带在冻融转换时需释放或吸收大量热量，从而在多年冻土对气候变化响应时起缓冲甚至热阻作用；其热阻抗因地下冰长期积累和增厚而加强，亦因地下冰的消融消耗而减弱，这些已被相关观测和模拟所证实（Scherler *et al.*, 2013；Luo *et al.*, 2018a；Wang *et al.*, 2023）.过渡带作为活动层与浅表多年冻土上部接触区，是活动层厚度和多年冻土热状态变化的调节器，随透镜冰、脉冰和分凝冰等的消长而变化，在短期气候波动中起保护冻土的作用（Shur, 1988）.对于高温多年冻土（年均地温＞－1 ℃），过渡带能够减缓冻土退化（Biskaborn *et al.*, 2019），表现为多年冻土退化时的下限抬升速率超过了上限下降速率（Li *et al.*, 2008；Luo *et al.*, 2018b）.地下冰在气候变暖时部分融化，活动层增厚，但在条件适宜时又会复原.这是因为活动层厚度对其自身变化的调节而有重现周期，其最大值或50年一遇或100年一遇，其中少冰冻土的活动层响应气候变化较快，而富含冰冻土的活动层变化相对稳定（Shur *et al.*, 2005；罗栋梁等，2023）.活动层厚度为多年平均值的概率最大，这是因为冰积聚时热阻抗会增加，其融化需更多热量，该量为沉积物质量和相变潜热的乘积（Shur *et al.*, 2005；Marmy *et al.*, 2013），因而融化到超过平均深度的概率也会降低（Shur *et al.*, 2005；罗栋梁等，2023）.由此可见，过渡带厚度是维持多年冻土热稳定的重要表征.

然而，目前表征和预测冻土融化的诸多模式和方法，多数欠缺对过渡带真实热物理性质的细致考虑，因而对变化环境下浅表层冻土变化的模拟预估存在失真，这必然夸大多年冻土热状况对气候变暖的响应（Lawrence and Slater, 2005；Lee *et al.*, 2014；Cai *et al.*, 2020；Lacelle *et al.*, 2022）.如Lawrence and Slater（2005）基于CLM模式和未来情景资料模拟，提出到本世纪末全球多年冻土退化至仅剩100万km^2，其结果引起一片哗然.Lawrence and Slater（2005）的过模拟固然欠缺对植被和土壤有机质的考虑（Yi *et al.*, 2007），其对过渡带热物理性质的忽略也是重要原因（Bockheim, 2015）.Lee *et al.*（2014）虽在过程模型中考虑了地下冰及

其相变潜热效应，但其地下冰数据来源于分辨率较粗的环北极多年冻土和地下冰分布图（Brown *et al.*, 1997），而欠缺对地下冰属性的实际调查和实验数据（Lee *et al.*, 2014）. 因此，亟待加强过渡带结构属性与宏观因素（纬度、海陆差异和海拔）和局地因素（微地形地貌、水文地质、植被、积雪等）的耦合研究，在冻土过程模型中定量考虑过渡带热物理属性与冻土热稳定性的相关性以实现其精准模拟（Lee *et al.*, 2014；Staub *et al.*, 2015；Pruessner *et al.*, 2018；Cai *et al.*, 2020；Wang *et al.*, 2020）.

3.4 过渡带变化的灾害效应

过渡带在地下冰加积和地表生态演替过程中形成，因富含地下冰特别是过剩冰，是多年冻土退化并产生热融沉陷和热融滑塌的重要原因（Shur and Jorgenson, 2007），即 Armstrong McKay（2022）所指的多年冻土突然融化和坍塌. 多年冻土地貌景观变化与冻融过程密切相关，主要存在两个时间尺度，一是浅地表冻土的季节冻融过程，一是过渡带的年际甚至是百年际尺度的冻融过程，两者均表征为活动层的增厚或减薄（图 6）. 可以预见的是，随着气候进一步变暖，活动层增厚，过渡带将大量变薄甚至消失（Paul *et al.*, 2021；Zwieback and Meyer, 2021）. 近年来，因过渡带的失稳和变薄进而导致热融灾害被广泛报道（Gruber, 2020；Zwieback and Meyer, 2021；Hayes *et al.*, 2022）. 如 2013—2018 年的遥感和实地观测表明，俄罗斯亚马尔 2016 年暖夏的沉降是其他年份的 2 倍（Bartsch *et al.*, 2019），暖冬和积雪增厚对地表能量交换的改变又限制了冻胀（Streletskiy *et al.*, 2017）. 基于 InSAR 技术的研究表明，极端气候事件频发，导致阿拉斯加西北坡富含冰多年冻土在高温夏季的沉降达 4～8 cm，而少冰冻土的沉降仅为 1～2 cm（Zwieback and Meyer, 2021）. 此外，地下冰融化造成山坡上当前地表以下的融化不整合面位置变化（Burn, 1997），引发最大融化深度以上形成大量热融滑塌（Lewkowicz and Way, 2019；Lim *et al.*, 2020）.

多年冻土在外界压力载荷下的应力传导，在很大程度上受过渡带地下冰类型及其含量影响. 比如在矿物质或有机质悬浮其间的地下冰中，应力只通过冰基质传导，而在地下冰与土岩接触的孔隙冰中，由于胶结冰只部分填充了土颗粒间的孔隙，应力则通过土颗粒间的接触传递（Murton *et al.*, 2004）. 随着多年冻土过渡带的融化固结和沉降，应力传导路径发生变化，因而在气候变暖时易产生诸多次生地质灾害如热融冲沟、热融坍塌、融冻泥流、热融滑塌、活动层滑脱等，使寒区工程结构失稳并可能造成重大的经济损失和环境风险（Lewkowicz and Harris, 2005a, 2005b；Mutter and Phillips, 2012；Farquharson *et al.*, 2016；Luo *et al.*, 2019, 2022a, 2022b；Mu *et al.*, 2020）. 实际上，活动层下伏富冰过渡带的变化是斜坡上岩石或沉积物及其所承载工程构筑物在暖季失稳的根源之一（Lewkowicz, 2007），冻土融化的致灾程度与过渡带的层位、含量及空间分布等密切相关. 过渡带通常包含大量过剩冰，易在极暖夏季融化而在地表产生热融沉陷，是多年冻土快速退化的标志，对桥隧道路等基础设施产生不利影响，但其细微变化在野外较难观测（Zwieback and Meyer, 2021）. 过渡带变化引起的灾害，包括在平原低地由冻融作用引起的沉陷，以及在斜坡地带由重力作用引起的近地表沉积物滑移（如水土流失、活动层滑脱和斜坡失稳）. 尽管因地下冰以及过渡带变化产生的热融灾害长期危害寒区基础设施，但尚缺乏对多年冻土过渡带结构和性质的精准估算，这也严重限制了对寒区生态系统和水文循环及多年冻土区社会经济可持续发展的准确预测（Heginbottom, 2002；Farquharson *et al.*, 2016；Melvin *et al.*, 2017；Ma *et al.*, 2021；Li *et al.*, 2022；Pan *et al.*, 2022）. 在气候变暖特别是极暖湿夏季驱动下的多年冻土活动层加深，使过渡带地下冰融化，多年冻土上部力学性能弱化，导致热融灾害在一定坡度地带下更易发生，因此需结合野外观测和建模，将深层融化与过渡带内的剪切位移及力学性能变化联系起来，加强活动层稳定性、热融灾害与冷生土壤剪切强度的相关研究（Lewkowicz and Clarke, 1998；Harris and Lewkowicz, 2000）.

4 总结

多年冻土是地球气候系统关键的气候临界要素之一，过渡带是多年冻土分层结构的重要组成，是预估多年冻土系统对气候变化、人类活动扰动响应的关键层位. 将过渡带作为多年冻土三层分层体系的组成部分，综合研究其结构特征、热物理性质和力学性能，对于明晰冻土与生态环境乃至寒区工程施工运维的互作有重要意义. 当前，国内外虽然在地下冰分布的地带和非地带性因素、地下冰类型

及其成因、冷生构造及气候环境指示等方面取得一定进展,但对过渡带的空间分布规律及其特征的系统性研究却是空白,特别是过渡带对气候变化的响应机制仍不明晰,相关冻土模型和方法也缺少适用的过渡带热物理性质.因此,亟待开展过渡带分布与形成机制、物源性质及其气候环境指示、对多年冻土热稳定性及其灾害效应的系统研究.以过渡带基本特征为出发点掌握地下冰演化对多年冻土环境与工程的改变,是开展寒区工程修筑运维和促进高寒脆弱生态环境可持续发展的关键.

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