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加拿大案例探讨寻找金刚石矿的三个关键点

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内容提要：20世纪90年代初，加拿大地质学家Charles E. Fipke先生在加拿大高寒的Lac De Gras地区发现的含金刚石的金伯利岩，把加拿大带入了寻找金刚石矿的高潮，相继在Lac De Gras地区发现金伯利岩管群和在加拿大中部的Fort à la Corne发现的金伯利岩群，使得加拿大金刚石产量位居世界第三。本文综述这两个地区金刚石矿的发现和分析含金刚石的金伯利岩的存在的特征，指出太古宙地台环境是含金刚石的金伯利岩存在的基础，厚度大的太古宙地台底部是金刚石晶体缓慢生长的天然高温高压培育仓、沿冰碛或沿水系沉积物追踪金伯利岩指示矿物是溯源金刚石母岩的手段、认识金伯利质火山地貌形态能起到在寻找金伯利质火山位置过程中事半功倍的效果，有助于理解金伯利质火山口相的变化。

关键词：加拿大；金刚石矿；Ekati；玛珥-管道火山体；金伯利岩指示矿物

自从1965年在山东蒙阴的常马庄和1971年在辽宁复县发现含金刚石的金伯利岩体，中国在50年内寻找含金刚石的金伯利岩体上始终没有大的突破(Song et al.，2019)。最近几年在印度南部发现了21个金伯利岩管(Phani，2019)和在加拿大萨省的中部发现的70个金伯利岩管群(Chalapathi Rao et al. 2017)是对中国地质工作者的一个激励。含有金刚石的金伯利岩(diamondiferous kimberlite，DK)是非常有价值的地质体、是上地幔信息的载体，持续为各国地质科学家所关注(Ault et al.，2015；Bailey et al.，2015；Heaman et al.，2015；Kamenetsky et al.，2014；Kamenetsky et al.，2015；Tappe et al.，2013，2014；Willcox et al.，2015；Stern et al.，2016)。寻找和发现中国土地中的DK是几代中国地质科学家的梦想，如果能在中国发现DK，那不只是经济利益和解决就业问题，最主要的是激励中国地质工作者的士气和寻找金刚石矿的信心。本文通过研究加拿大两个地区的DK，研究它们在大地构造环境、指示矿物、地貌的特点，讨论寻找DK过程中的关键点。

1 加拿大寻找金刚石矿案例

1899年Hobbs先生认为加拿大安大略和魁北克省的水系沉积物中所发现的金刚石是来自北部的高寒地区，是冰川向南搬运的结果。20世纪60年代加拿大许多地质学家开始在北部高寒地区寻找金刚石矿，但是三十年中没有发现任何线索(Kjarsgaard et al.，2002)，1977年开始长达20年寻找的地质学家Charles E. Fipke先生发现了Ekati矿，加拿大进入了寻找DK的高潮期，随后在Ekati矿的南部发现了Diavik矿，至今在这两个矿所在的Lac De Gras(LDG)地区，用物探方法发现了400个金伯利岩管(一些被冰河覆盖的岩管没有得到取芯验证)。最近20年，在加拿大中部的萨省的Fort à la Corne(FALC)地区发现了70个金伯利岩管群。2016年，加拿大开工的金刚石矿山有Ekati、Diavik(图1a)和Victor金刚石矿，2015年加拿大金刚石产量为1160万克拉，2016年生产出价值16.74亿美元的金刚石(www. kimberleyprocess. com/en/canada)，产量在俄国和博兹瓦纳之后(Zimnisky，2017)。

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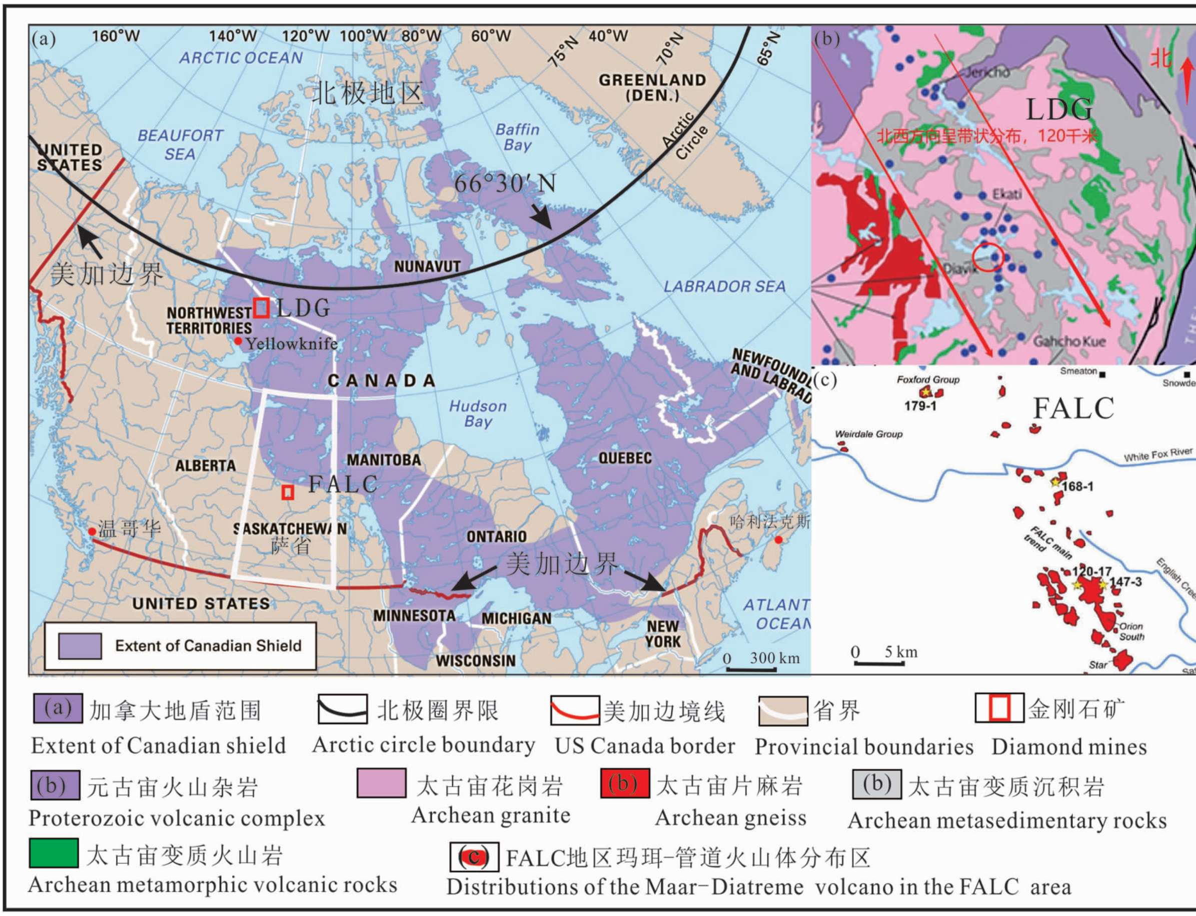

图 1 加拿大地盾分布图，LDG 和 FALC 地区金伯利岩分布图

Fig. 1 Range of Canadianshield, kimberlite distributions in LDG and FALC regions

(a)—加拿大地盾的分布范围、LDG 和 FALC 金伯利岩群的位置(据 Encyclopaedia Britannica Inc. 修改)；(b)—Ekati 和 Diavik 矿(红圈位置)位于 LDG 地区金伯利岩群的中部，金伯利岩群呈北西向延展，位于太古宙岩石组成的 Slave 地台中(据 Shigley et al.，2016 修改)；(c)—加拿大萨省的中部 FALC 金伯利岩体群(据 Chalapathi Rao et al.，2017 修改)

(a)—Distribution range of Canadian Shield, locations of LDG and FALC kimberlite group (modified from Encyclopaedia Britannica Inc.); (b)—Ekati and Diavik mines (red circle location) are located in the middle of kimberlite group in LDG area with extension of northwest direction in the slave craton composed of Archaean rocks (modified from Shigley et al., 2016); (c)—the kimberlite group in the FALC, central Saskatchewan, Canada trending in NNW (modified from Chalapathi Rao et al., 2017)

1.1 Ekati 金刚石矿

1977 年地质学家 Charles E. Fipke 先生在没有资金支持的情况下，开始在加拿大北部的 LDG 地区追踪金伯利岩分离出的微量的重砂矿物，具有加拿大 UBC 大学学士学位、赛马运动员、年轻时被认为非常笨的人，对寻找金伯利岩执着和怀有坚定的信念，他尤其善于区分哪种榴辉岩的石榴子石指示 DK 的追踪方向，他和合作伙伴 Stu Blusson 博士在 20 年中几起几落、分分合合、受资金的困扰、几进几出加拿大北部高寒无人区，冒着各种风险追踪金伯利岩指示矿物，寻找金刚石矿(人物传记作家 Cross(2011)出版《冻土下的宝藏》详细生动地描述了 Fipke 先生发现金刚石矿的全部过程；Everything(2020)客观介绍了 Fipke 先生)。至 1990 年 4 月，长达 13 年在高寒无人区冻土上孤独行走的 Charles E. Fipke 先生，在 LDG 地区(图 1a)的重砂样品中发现了镁铝榴石和透辉石，经过矿物化学分析，他认为金伯利岩体就在附近，随即他和 Stu Blusson 博士共同注册探矿权 (Fipke et al., 1995)。他所发现的三个金刚石矿体的规模都不大，但金刚石的品位高，应当属于第 III 种类型的(即：没有火山管道相)金伯利岩管(丁毅，2019)。

1991 年 BHP 勘探金刚石矿的专业公司在 Ekati 金伯利岩体内取得 59 kg 的金伯利岩芯，居然从中分选出 81 颗宝石级金刚石，随机取样却有这样的高品位，这在世界金刚石矿勘探历史上是第一次。

从 1992 年起,加拿大进入了寻找 DK 的高峰期(the biggest land rush. Krajick, 1994, 2001; Boyd, 2006),在 Ekati 金伯利岩体附近发现了 150 座金伯利岩,多呈“胡萝卜”管形状,现在开采的有 5 座,岩体形成的年代在 45 ~75 Ma。Ekati 矿是目前加拿大高效的金刚石矿,年产 7 百万克拉的金刚石,以金伯利岩体小但品位高而著名,Ekati 矿和 1995 年在 Ekati 矿东南部发现的 Diavik 矿,估计总共藏有约 190 亿美元价值的金刚石 (Kjarsgaard, 2007)。但是,建造该矿山是一个极大的挑战,面临加拿大北部高寒地区、有许多破坏金伯利岩管的岩墙穿过(Olive et al. ,2004)、清干湖水、异地建立金刚石分选工厂等方面的问题,高品位和高质量的金刚石产出使得矿山保持资金安全和获利地生产,可以保障到 2024 年。在建造这一北部高寒地区矿山的过程中,加拿大政府和各个金刚石矿山公司先后投资 13 亿加元用于评估、建造后勤补给基地、建造运输矿石路、在异地建造分选工厂等。从 Ekati 矿中产出一颗 186 ct 的金刚石,从 Diavik 矿中先后分选出 187.7 ct 的金刚石(命名为 Diavik Foxfire, 图 2e) 和 151 ct 的金刚石 (Tupper et al. , 2002)。

在 LDG 地区近 30 年中的找矿中,超过 400 个金伯利岩管被相继发现,金伯利质岩管呈北西方向延展 120km (Carlson et al. , 1999)。Ekati 金刚石矿位于加拿大 Slave 地台内,Slave 地台(Isachsen et al. , 1994) 是加拿大前寒武纪地盾 (Canadian Shield)的一部分,加拿大地盾自太古宙以来没有遭到破坏,北部高寒地区还有 2 万年累计的冰盖覆盖(Bleeker, 2002; Davis et al. ,2003; Canil, 2008)。几条元古宙辉绿岩脉穿过些花岗岩中的构造薄弱带,这些构造薄弱地带可能是金伯利质岩浆上侵和爆发冲出地表的地方。Ekati 金刚石矿的金伯利岩管及其周围面积 2 万 m^2,岩管延伸至少 600 m 的深度,每一管道内的岩石都是由不同类型的金伯利岩和围岩混合而成,火山管道上部被一层薄薄的湖泊沉积物和 15~20 m 厚的湖水所覆盖(Graham et al. , 1999; Bryan et al. , 2003; Moss et al. , 2008)。岩管上部的火山口相由金伯利质火山碎屑岩和围岩的混合物组成,形成年代是 55 Ma 前的始新世(Graham et al. , 1999)。通过对 Ekati 金刚石矿和附近的 Diavik 矿中宝石级金刚石中的硫化物矿物包裹体研究,采用铼到锇的放射性衰变的测年方法,得出金刚石晶体的形成期大约为 33 亿到 35 亿年前,可能是世界上最古老的金刚石(Westerlund et al. , 2006; Aulbach et al. , 2009)。

1.2　Fort à la Corne 金伯利岩管群的发现

Fort *à* la Corne (FALC)金伯利岩管群位于加拿大萨省的中部地区(图 1a),金伯利岩中钙钛矿 U-Pb 法和金云母的 Rb-Sr 测定 FALC 金伯利岩管群在 99 ~ 106 Ma 年间 (Zonneveld et al. , 2004; Berryman et al. ,2004; Kjarsgaard et al. , 2009),金伯利质岩浆侵入至陆地沉积(Mannville Group) 和海洋沉积环境 (Lower Colorado Group), 70 座岩管形成宽 10km、长 35km 北北西方向延伸的金伯利岩省。FALC 金伯利岩管群位于 Sask 地台内,地震波数据显示 Sask 地台与北部的 Slave 地台、东部的 Rae 地台和 Superior 地台同属于加拿大地盾(Jones et al. , 2003; Snyder et al. , 2010),捕虏体中锆石年龄测定 Sask 地台的年龄在 3100~2450Ma 之间 (Bickford et al. , 2005)。

在地貌上,这片金伯利质火山口与南非和中非所报道的完全不同,个别火山口相岩石的分布超出火山口之外,被描述为香槟-玻璃杯形状 (图 2f, Berryman et al. , 2004),火山口直径达 2000m,这在金伯利岩研究记录上是少见的(Scott Smith, 2008),而 Kjarsgaard et al. (2007) 认为金伯利岩体的剖面形状还是属于多次爆发成因的火山碎屑锥形状 (图 2g-(b))。金伯利质火山口的形状有近直立岩管(Steep sided pipes)和正地形火山口(scoria or tuff cones, 图 2g-(a)、(b))。1988 年在该地区发现了金伯利岩后,进行了大面积的磁法测量,先后发现了 70 个高磁异常圈点,1989 年对其中 7 个目标取芯验证均为含金刚石的金伯利岩,1990 年和 1991 年间获取 39 个大样(bulk samples)代表 3601 个取样点,分选出 160 颗金刚石,平均 0.04 克拉,最大的一颗为 0.6 克拉,39 个大样平均品位为 2 克拉/百吨,160 颗金刚石以宝石级为主(Lehnert-Thiel et al. ,1992)。对这群金伯利岩的进一步钻探取芯表明 70%的金伯利岩含有金刚石。

岩芯显示上部为金伯利质火山口相,由未完全固结的堆积沉积岩、火山砾组成,其中含有橄榄石、石榴石、镁钛铁矿、橄榄石(橄榄石的矿物化学显示以镁橄榄石为主 (Fo87-92), NiO (0.16% ~ 0.38%),CaO(0.04%~0.14%),颗粒的数量不等,火山砾的形状从球形到变形虫形状都有,显示出它们是在高度流动的岩浆中形成,细小的矿物有金云母、尖晶石、碳酸盐矿物、钙钛矿和金红石,被碳酸盐化和蛇纹石化细纹脉交织在一起 (Scott-Smith,

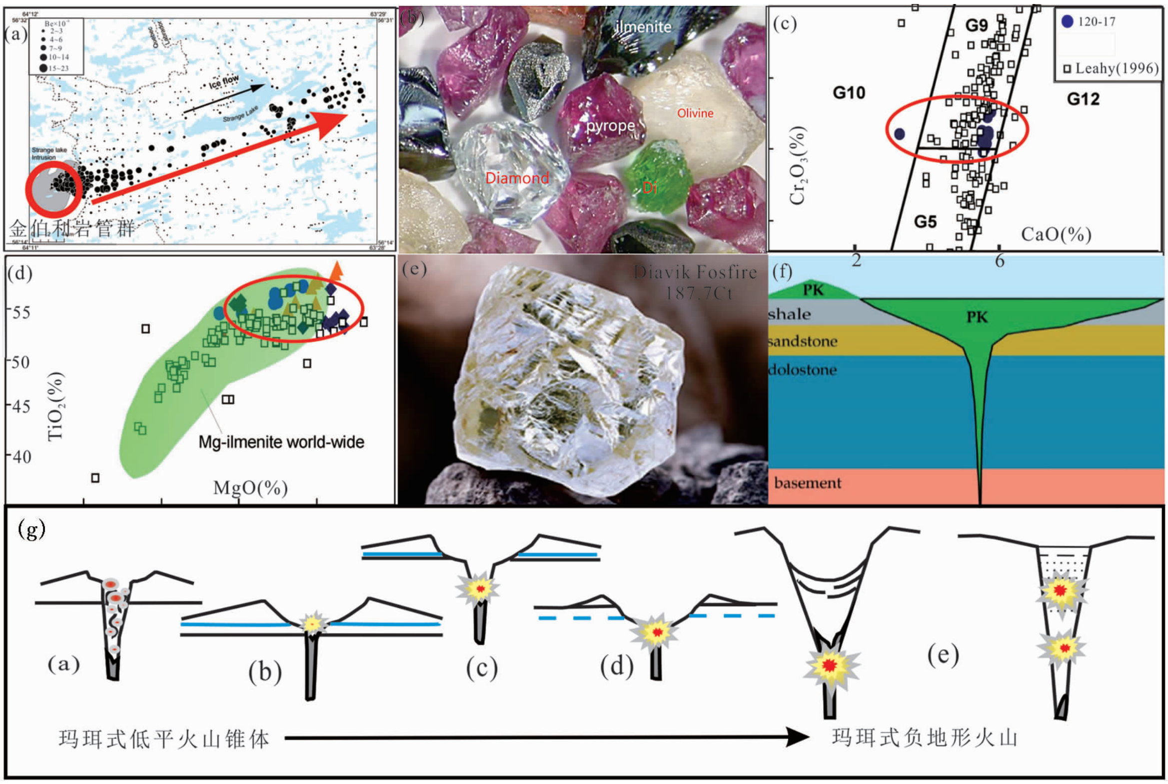

图 2 金伯利岩指示矿物和金伯利岩地貌特点

Fig. 2 Indicator minerals and geomorphic characteristics of kimberlite

(a)—从 DK 剥离出来的 KIM 通过冰川和河水叠加搬运到达 30000 m 远的地方(McClenaghan et al., 2000);(b)—DK 指示矿物:玫瑰红色是镁铝榴石,透明的是金刚石,发黄的白色半透明的是橄榄石,黑色的是钛铁矿,绿色的是透辉石;(c)—FALC 分选出的镁铝榴石投影位置图(Chalapathi Rao et al. (2017) based on Grütter et al., 2004);(d)—FALC 分选出的钛铁矿投影位置图(Kaminsky et al., 2004,据 Leahy,1996);(e)—从 Diavik 矿选出的 Diavik Firefox, 187.7 ct (Shigley et al., 2016);(f)—典型的金伯利质火山口相的直径小于 1000 m,而 FALC 中部 147 号岩管为直径较宽的百合长笛香槟杯形状(Lily Flute Harveys Champagne Glass,Field et al., 1999);(g)—金伯利质火山口有正地形也有负地形,最多的地形是玛珥-管道火山形状 (Maar-diatreme volcano) (据 Kurszlaukis and Lorenz,2017 修改)

(a)—KIM stripped from DK reaches 30000m away through the complex and mixed transportation by glaciers and rivers (Mcclenaghan et al., 2000); (b)—KIM: rose-red pyrope, transparent diamond, yellow-white and translucent olivine, black ilmenite, green diopside; (c)—selected pyrope from FALC in CaO-Cr_2O_3 diagram (Chalapathi Rao et al., 2017), based on Grütter et al., 2004); (d)—selected ilmenite from FALC in MgO-TiO_2 diagram (after Kaminsky et al.,2004), based on Leahy,1996); (e)—Diavik Firefox, 187.7 ct. (Shigley et al., 2016); (f)—the diameter of typical kimberlitic crater facies is less than 1000m, while the 147 kimberlite in the middle of FALC is wider with the shape of "Lily flute Harveys champagne glass"(Field and Scott Smith,1999); (g)—kimberlitic crater has positive and negative terrain, the most is maar-diatreme volcano (after kurszlaukis and Lorenz,2017)

2008)。橄榄石斑晶、火山砾、其他微小的矿物广泛被蛇纹石化和碳酸盐化交代,含有相当比例的挥发物参与火山喷发。从玢岩相岩石中测得 Nd 同位素在+0.62~−0.37,CaO 小于 5%和较高的 La/Sm 比值(12~15)为特征,排除了地壳物质混染的因素(Chalapathi Rao et al., 2017)。

因为金伯利岩火山口相和火山管道相都含有大量的壳源捕虏体,全岩化学分析的挑选和粉碎样品过程中要特别注意剔除各种包体,尽量挑选玢岩相样品(Ding, 2019)。FALC 金伯利岩管群岩石化学成分变化为:SiO_2 = 21.5% ~ 36.3%; Al_2O_3 = 0.92%~5.84%; MgO=16.9%~34.5%; TiO_2 = 0.90%~8.51%; Fe_2O_3 = 7.29%~18.8%和 CaO = 12.3%~25.6%(Chalapathi Rao et al., 2017)。

2 讨论

2.1 稳定的地台是含金刚石金伯利岩体存在的前提

1829 年的沙皇俄国时期,人们在乌拉尔含金砂矿中发现了第一颗金刚石,此后的 100 年中,地质工作者一直在苦苦地寻找金刚石的原生矿。1937 年,地质学家 B C 索波列夫对比西伯利亚地台和南

非地台后,发现它们具有明显的相似性,于是把注意力集中在西伯利亚地台上。1945 年,前苏朕的地质工作者开始在西伯利亚地区寻找金刚石矿,经过十年的对指示矿物的追索,发现了第一个金伯利岩岩管,此后又在该区附近发现了金伯利岩岩管群。Field et al. (2008) 全面分析了非洲的 34 个金刚石矿后认为,金刚石矿都赋存在太古宙地台内。本文所介绍的加拿大 LDG 和 FALC 这两个金伯利岩群区也有一个共同的特点:它们都位于加拿大地盾中的稳定的地台内。正在开采的 Ekati 和 Diavik 矿所处的 LDG 地区位于 Slave 地台内,由花岗岩、片麻岩、中生代的火山岩、变质沉积岩组成,形成年代在 2.63 ~ 2.58 Ga (van Breemen et al., 1992; Nowicki et al., 2004),太古宙镁铁岩脉群侵入年代在 2.23～1.27 Ga (LeCheminant et al., 1994),在 LDG 地区还发现有古老的 42 亿年的岩石(Bleeker, 2002; Helmstaedt, 2009)。

Janse (1985)发现含金刚石的金伯利岩都在 A 型克拉通内,并认为大于 2400 Ma 基底已固化的太古宙的 A 型克拉通是含金刚石金伯利岩存在的条件。A 型克拉通地台的特点是长期稳定和存在厚度大于 150 km 的古老地层(Ringwood et al., 1992)。加拿大 Ekita 和 Diavik 是始新世时期金伯利质岩浆裹挟着在地下深处某一岩石层中的金刚石晶体(太古宙晶体,Donnelly et al., 2007),上侵冲破地表爆发形成火山口并充填火山岩管,太古宙的 A 型克拉通厚度大,其底部的高压环境是培育金刚石生长的良好环境,换句话说太古宙地台底部是一个金刚石晶体缓慢生长的天然高温高压培育仓。

2.2　指示矿物追踪

利用金伯利岩指示矿物(Kimberlite Indicator Minerals, KIM)追踪 DK 是各国地质学家采取的简单和有效的办法。加拿大高寒地区冰川运动(图 2a)搬运 KIM 可达 30 km 的距离,而且分选性不如河流搬运的分选性好。持续追踪和详细统计矿物种类和数量,建立可视化图表是通常采用的方法(Chalapathi Rao et al., 2000)。上面介绍的寻找 Ekati 金刚石矿过程中,Charles E Fipke 先生就是非常重视重砂矿物的追踪,发现镁铝榴石、绿色的透辉石、黑色的钛铁矿和黑色的尖晶石都是有意义的(Gurney, 1984; McClenaghan, 2005; Shirey et al., 2013)。然而,许多不含金刚石或不具有开采意义的岩体也含有类似 DK 中 KIM 的矿物,这样的岩体包括不含金刚石的金伯利岩和岩脉、低品位的钾镁煌斑岩、榴辉岩、基性-超基性岩(苦橄玢岩等),但是它们的矿物化学成分是与 DK 中 KIM 的矿物化学成分是有区别的(Boyd et al., 1982; Fipke et al., 1995; Schulze, 2003; Wyatt et al., 2004; Cookenboo et al., 2007; Xu et al., 2017)。在追踪来自 DK 的 KIM 过程中,通过对分选出的矿物进行化学分析,与已知 DK 矿物化学相对比,就可以区别所挑选出来的疑似 KIM 是来自 DK 还是来自如上所列出的干扰体(Westerlund, 2005; Ding et al., 2019)。经过全球科学家不懈的努力,用数据-图表化的手段是可以区分这些矿物,它们是来自干扰体、来自钾镁煌斑岩、还是含金刚石的金伯利岩(Cookenboo et al., 2007; Grütter et al., 2004; Grütter et al., 2006; Quirt, 2004; Wyatt et al., 2004)。在追踪 KIM 过程中,应当重视对 KIM 的解读和反复研判,视其为非常重要的工具,确定在一个地区是否有继续开展寻找 DK(Gregory et al., 1989),把分析 KIM 作为手段排除干扰体,为及时纠正偏差、及时调整方向、及时更改计划提供决策依据。

2.3　金伯利岩的地貌特征

研究金伯利岩火山的地貌形态,通过卫星影像数据和野外地质调查判断金伯利质岩管的位置能起到事半功倍的效果,也是认识金伯利质岩管的基础。目前许多学者共同认识,在地貌上金伯利岩体是玛珥-管道火山岩体(Maar-diatreme volcano, Barnett, 2008; Kurszlaukis et al., 2017)。玛珥式火山口依据德国境内存在的玛珥湖的地貌而得名。研究表明:部分基性岩火山口、超基性岩火山口、金伯利质火山口从地貌形态上都是玛珥式火山口(Barnett, 2008; Kurszlaukis et al., 2017; Ding et al., 2019)。这样类型的火山口,在世界上不同地区存在有高出地面的正地形火山、不高的低矮火山渣堆、完全负地形的火山口。坦桑尼亚所发现的全新世金伯利质火山口为保存完好的正地形(Brown et al., 2012),本文介绍的加拿大萨省 FALC 白垩纪金伯利质火山口群受风化破坏小,地貌形态多种多样,有正地形也有负地形(Lefebvre et al., 2008),乌兰察布市境内的玛珥式火山口全部为负地形(Ding et al., 2019)。形成负地形的火山口在最初形成火山口时喷出极少岩浆和以水汽喷发为主的火山活动,因此在这样的火山口内外不存在激浪火山碎屑沉积(Unbedded Lefebvre et al., 2013),它是一种火山射汽喷发活动。负地形的玛珥式-管道火山岩体就是岩浆遇到

地下水形成气液岩浆,上侵时遇到阻挡层时地下岩浆房内部蒸汽压加大,导致地下爆炸而形成地堑式塌陷的结果(Valentine et al., 2014; Houghton et al., 2015; Kurszlaukis et al., 2017)。

金伯利质火山岩浆爆发是具有二氧化碳和水的超基性岩浆火山爆发(Blaikie et al., 2015; Kurszlaukis et al., 2017)。岩浆上侵到近地表时,地下水参与的量不同导致形成不同的火山地貌(Gernon et al., 2009; Kurszlaukis et al., 2013; Hamblin, 2015; Fanasye et al., 2014; Lorenz et al., 2017),地下水参与火山喷发越多,为射汽喷发(phreatic),形成以射汽上冲形成火山口、岩浆充填管道的玛珥式-管道火山岩体,地貌上形成负地形火山口;岩浆上侵过程中地下水加入少,火山喷出地表的碎屑量大,为射汽岩浆喷发(phreatomagmatic),地貌上形成不高的正地形玛珥式火山口(Barnett et al., 2007;Lorenz et al., 2007; Cas et al., 2008; Valentine et al., 2012; Blaikie et al., 2015; Houghton et al., 2015; Kurszlaukis et al., 2017; Ding et al., 2019)。

3 结论

加拿大 LDG 地区和 FALC 地区都位于加拿大地盾内,稳定的地台环境是含金刚石的金伯利岩体存在的前提,太古宙地台底部是一个金刚石晶体缓慢生长的天然高温高压培育仓。

金伯利岩所含有的矿物是在高温高压的上地幔形成的,在地表的低温低压的环境中失去平衡而裂解。既使正地形的金伯利岩火山堆早就被风化而消失,火山口沿处或喷出到火山口外的 KIM,被风化剥蚀的管道相所分离出的 KIM 形成分散晕,金伯利岩体中的金刚石、镁铝榴石、铬铁矿和钛铁矿物的物理稳定性高,它们的抗风化的能力要比岩石中的橄榄石、辉石和金云母强得多,追踪 KIM 和及时分析它们的矿物成分是寻找含金刚石的金伯利岩的一种重要手段。

除了少数金伯利岩呈岩脉产出,大多数金伯利岩浆是以中心式火山喷发形成低平圆形地质体,玛珥-管道火山岩体无论是不高的正地形或低于地面的负地形都应当值得重视和研究。在这个基础认识上,无论在野外调查和室内卫星影像资料的解读中,都要注意超基性岩火山地貌风化后的表现。事实上,过去猛烈的金伯利火山爆发在地表或多或少会留下痕迹的。

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A discussion on key points in diamond prospecting based on case studies in Canada

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Abstract

The discovery of diamondiferous kimberlite in the cold Lac De Gras area of Canada by the Canadian geologist Charles E. Fipke in the 1990s crowned extensive efforts to locate this mineral. The kimberlites were found in the Lac De Gras and the Fort à la Corne areas in the central part of Canada, resulting in its becoming the third largest diamond producer. This paper compiles data on the discovery of diamond deposits in these two areas and analyses their characteristics. It highlights the fundamental role of the Archean craton in the formation of diamondiferous kimberlite. The thick bottom of the Archean platform is a natural high-temperature and high-pressure incubator for the slow growth of diamond crystals. The tracing of kimberlite indicator minerals in glacial and/or fluvial deposits is a useful technique to trace diamondiferous kimberlite. Documenting the morphology of kimberlite volcanoes can also boost efforts to trace changes in kimberlite crater facies.

Key words：Canada，diamond mine；Ekati；Maar-diatreme volcano；kimberlite indicator minerals