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敦煌地块敖包山晶质石墨矿集区矿床地质特征、变质岩原岩恢复及形成环境

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摘要:【研究目的】为解决敦煌地块敖包山晶质石墨矿集区晶质石墨矿床研究程度较低的问题, 通过对该区变质岩原岩特征及古构造环境进行深入研究, 以期为该区的成矿规律研究提供地质依据。【研究方法】本文运用岩石地球化学方法对该区变质岩进行原岩恢复, 探讨其形成时的古构造环境。【研究结果】二云石英片岩、黑云斜长片麻岩和斜长角闪岩均具有轻稀土富集的特征。斜长角闪岩 $K_2O < Na_2O$, 具有弱的 Nb、Ta 亏损和强烈的 Zr、Hf 亏损, LREE/HREE=2.21~6.97, 轻重稀土元素分馏程度较弱; 黑云斜长片麻岩和二云石英片岩 $K_2O > Na_2O$, 富集大离子亲石元素 Rb、K 等, 亏损 Ba、Nb、Ta、Zr、Hf、Ti、Sr 等元素, 具有明显的 Eu 负异常, LREE/HREE 平均值分别为 12.44 和 8.89, 轻重稀土元素分异较强烈。【结论】敖包山晶质石墨矿集区变质岩原岩形成于浅水区, 水动力环境较弱。斜长角闪岩的原岩为亚碱性基性火山岩, 形成于岛弧环境; 二云石英片岩和黑云斜长片麻岩的原岩为页岩、黏土岩, 构造环境为活动大陆边缘, 古沉积环境为干燥气候带条件下富氧的海陆交互相, 古水体介质为半咸水。

关键词: 晶质石墨矿集区; 敦煌岩群; 变质岩; 原岩恢复; 敖包山; 敦煌地块; 甘肃省

创新点: (1) 运用岩石地球化学方法对敦煌地块敖包山晶质石墨矿集区进行变质岩原岩恢复; (2) 识别该区不同类型变质岩形成的古构造环境差异。

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Geological characteristics of the deposits, protolith restoration and paleoenvironment of the Aobaoshan crystalline graphite deposit concentrated area in Dunhuang block

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Abstract: This paper is the result of mineral exploration engineering.

[Objective] Due to the relatively low research level of crystalline graphite deposits in the Aobaoshan crystalline graphite deposit-concentrated area in Dunhuang block, the protolith restoration and paleoenvironment of this area are studied profoundly, which will provide a geological foundation for metallogenic regularity. **[Methods]** The protolith of the metamorphic rocks in the Aobaoshan crystalline graphite deposit-concentrated area is restored using the method of petrochemistry, and the paleotectonic environment of its formation is discussed. **[Results]** Two-mica quartz schist, biotite plagioclase gneiss and plagioclase amphibolite are enriched in the light rare earth elements. The plagioclase amphibolites have less K_2O contents than Na_2O . They are weakly depleted in Nb and Ta, and strong depleted in Zr and Hf, and have the ratios of LREE/HREE ranging from 2.21 to 6.97, indicating the weak fractionation degree of light and heavy rare earth elements. The biotite plagioclase gneisses and two-mica quartz schists have higher K_2O contents than Na_2O . They show the enrichment in large ion lithophile elements, such as Rb and K, and the depletion in Ba, Nb, Ta, Zr, Hf, Ti and Sr, and obvious Eu negative anomalies. The average ratios of LREE/HREE of the biotite plagioclase gneiss and two-mica quartz schist are 12.44 and 8.89, respectively, indicating strong differentiation of light and heavy rare earth elements. **[Conclusions]** It is inferred that the protoliths of the metamorphic rocks from the Aobaoshan crystalline graphite deposit-concentrated area were formed in shallow water area with weak hydrodynamic environment. The protoliths of the plagioclase amphibolites in the Aobaoshan crystalline graphite deposit-concentrated area are subalkaline basic volcanic rock, and they were formed in an island arc. The protoliths of biotite plagioclase gneisses and two-mica quartz schists are shale and clayrock, and they were formed at active continental margins. The paleosedimentary environment was oxygen-rich interactive marine and terrestrial deposition in dry climate zone, and the paleowater medium was brackish water.

Key words: crystalline graphite deposit-concentrated area; Dunhuang Group; metamorphic rocks; protolith restoration; Aobaoshan; Dunhuang block; Gansu Province

Highlights: (1) The protolith of the metamorphic rocks of the Aobaoshan crystalline graphite deposit-concentrated area are restored with methods of petrochemistry. (2) The paleotectonic environment differences of different types of metamorphic rocks of this deposit-concentrated area are identified.

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1 引 言

石墨是由碳元素(C)组成的自然元素矿物,根据结晶程度分晶质石墨(又称鳞片石墨)和隐晶质

石墨(土状石墨)两大类。美国内政部2018年发布35种关键矿产最终名单,其中包括天然石墨,2020年欧盟将天然石墨列入关键矿产清单。鉴于晶质石墨未来的利用前景和高度垄断性,目前主要经济

体已经开始调整其国际资源战略。晶质石墨也被《全国矿产资源规划(2016-2020年)》列为战略性矿产之一,中国既是石墨资源大国,也是生产消费大国(Ai et al., 2018; Sun et al., 2018; Duan et al., 2020; 何亮等, 2021; 宁括步等, 2022; 张艳飞等, 2022)。石墨具有耐高温、耐腐蚀、导电、导热、润滑、表面能低、重量轻、炭化收率高等多种特性,是支撑高新技术发展的重要战略物资,广泛应用于化工、冶金、机械、核工业、电子、航空航天、国防军工及新兴产业等领域(李超等, 2015)。它既是传统工业(耐火材料、铸造、摩擦密封)的原辅材料,更是节能环保、信息技术、生物医药、高端装备制造、新能源、新材料等产业的支撑材料。天然石墨是制备石墨烯的原料,石墨烯产业的蓬勃兴起引发对石墨的革命性需求,高新技术新兴产业(电子工业、航天航空材料

等)为石墨材料带来广阔的市场空间。

甘肃酒泉敖包山晶质石墨矿集区大地构造位置处于塔里木板块与柴达木—祁连板块的交接部位(图1a),次级构造属敦煌地块(刘永顺等, 2009; 张新虎等, 2013; 王楠等, 2016)。2016年以来,甘肃省地矿局四勘院在该矿集区开展了大量的晶质石墨勘查工作(赵吉昌等, 2021; 陈世强等, 2021),新发现晶质石墨矿床8个,已完成普查评价4个,均达大型规模以上,实现了甘肃省晶质石墨的找矿重大突破,使甘肃省晶质石墨资源跃居全国前列,其中敖包山晶质石墨矿普查被自然资源部评为2020年找矿突破战略行动优秀找矿成果。目前该区晶质石墨矿床的研究仅限于对矿体特征、成矿条件及找矿标志等的研究(王东升和马富平, 2017; 刘力等, 2019; 穆可斌等, 2019; 付全等, 2020; 王东升和刘

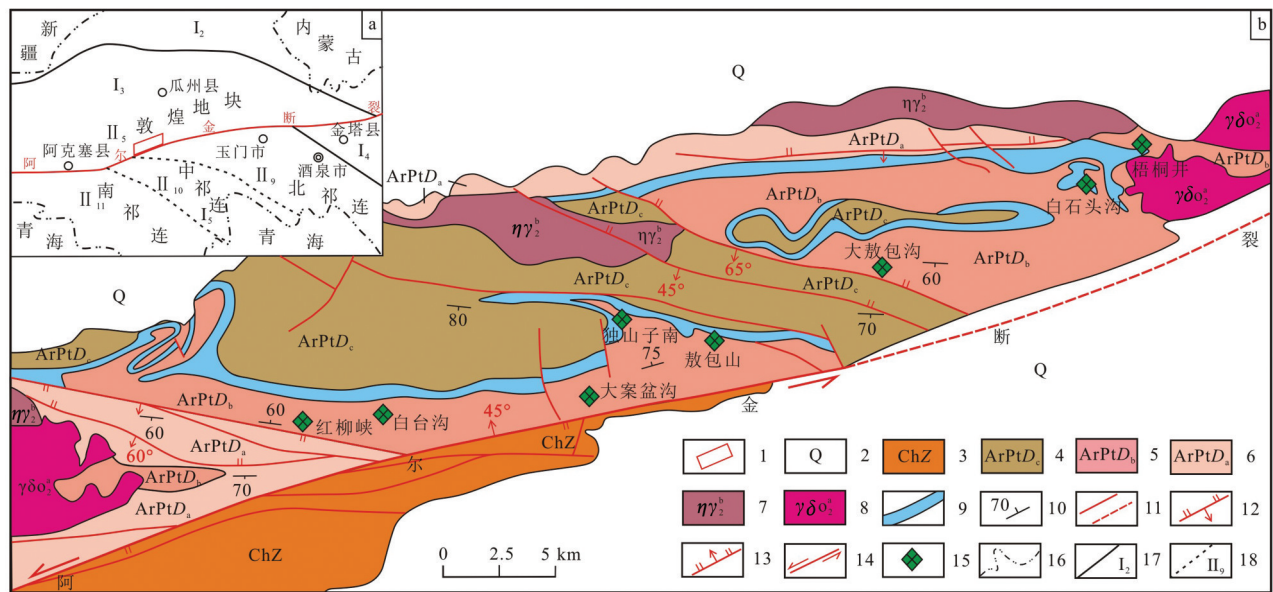


图1 敖包山矿集区地质简图(据贾鑫等, 2020)

1—研究区范围; 2—第四系; 3—长城系朱龙关群; 4—太古宇—古元古界敦煌岩群C岩组; 5—太古宇—古元古界敦煌岩群B岩组; 6—太古宇—古元古界敦煌岩群A岩组; 7—二长花岗岩; 8—英云闪长岩; 9—大理岩; 10—地层产状; 11—实测及推测断层; 12—实测逆断层; 13—实测正断层; 14—实测平移断层; 15—石墨矿床; 16—省界; 17—一级构造单元界线及编号; 18—二级构造单元界线及编号; I₂—哈萨克斯坦板块; I₃—塔里木板块; I₄—华北板块; I₅—塔里木—祁连板块; II₅—敦煌地块; II₆—北祁连早古生代褶皱带; II₁₀—中祁连中间地块; II₁₁—南祁连早古生代褶皱带

Fig.1 Geological sketch map of the Aobanshan deposit concentrated area(after Jia Xin et al., 2020)

1—Study area; 2—Quaternary; 3—Zhulongguan Group, Changcheng System; 4—C—rock member of Archean—Paleoproterozoic Dunhuang Group; 5—B—rock member of Archean—Paleoproterozoic Dunhuang Group; 6—A—rock member of Archean—Paleoproterozoic Dunhuang Group; 7—Monzogranite; 8—Tonalite; 9—Marble; 10—Stratigraphic occurrence; 11—Measured and inferred faults; 12—Measured reverse fault; 13—Measured normal fault; 14—Measured translational fault; 15—Graphite deposit; 16—Provincial boundaries; 17—Boundary and number of primary structural unit; 18—Boundary and number of secondary structural units; I₂—Kazakhstan plate; I₃—Tarim plate; I₄—North China plate; I₅—Tarim—Qilian block; II₅—Dunhuang block; II₆—North Qilian Early Paleozoic fold belt; II₁₀—Middle Qilian block; II₁₁—South Qilian Early Paleozoic fold belt

强,2020;贾鑫等,2020),对该矿集区变质岩系的原岩特征尚未进行系统研究。

恢复变质岩原岩类型,并探讨其古构造环境是寻找相关矿床的基础(周世泰,1984;王仁民等,1987)。运用岩石地球化学方法,采用地球化学稳定性较强、在地壳中广泛分布且有指示意义的主量元素及微量元素、微量元素比值及多元素图解法可以有效判别其原岩类型及形成的构造环境(周世泰,1984;Bhatia and Crook,1986;Jones and Manning,1994;邓绍军等,2020)。本文在对敖包山晶质石墨矿集区变质岩进行岩相学特征研究的基础上,运用岩石地球化学方法对该区变质岩进行原岩恢复,探讨其形成时的古构造环境,以期对敖包山晶质石墨矿集区的成矿规律研究提供地质依据。

2 区域地质概况

敦煌地块位于塔里木盆地东部,北接北山造山带,东南于阿拉善地块相邻,南以阿尔金断裂带与祁连山断开(赵燕等,2013)。敦煌地块较完整的保存了太古宙—古元古代的基底岩系,《甘肃省区域地质志》(甘肃地质矿产局,1989)将该套老变质岩系划分至敦煌群(AnChD),《甘肃省岩石地层》(杨雨等,1997)将其归并为敦煌岩群(ArPtD),划分为A、B、C、D四个岩组,后续各项研究调查工作基本沿用此划分方案。

研究区晶质石墨矿床赋矿层位均为敦煌岩群,赋矿岩性主要为二云石英片岩、白云母石英片岩,局部地段为大理岩、黑云斜长片麻岩;矿体的围岩也相同,均为含石墨白云母石英片岩、二云石英片岩、含石墨大理岩、黑云斜长片麻岩及斜长角闪岩。锆石U-Pb定年结果表明,斜长角闪岩原岩的结晶年龄为(1611±6)Ma(王忠梅等,2013)。矿石矿物为晶质石墨,呈显微鳞片—鳞片变晶结构,片状构造、稀疏浸染状构造分布于脉石矿物颗粒之间(图4a、b)。石墨片度主要在38~147 μm,工艺厚度较大,主要为10~20 μm。石墨与脉石矿物平直接接触,单体解离难度小,有利于获得较高的精矿品位。地表风化矿可获得石墨精矿固定碳含量为94.40%,回收率98.34%;深部原生矿可获得石墨精矿固定碳含量为98.01%,回收率99.22%,属于高碳石墨范畴^①。脉石矿物主要为云母、石英,其次为碳

酸盐集合体、黄铁矿、赤铁矿、褐铁矿等。

该套变质岩系的变质矿物组合为石榴石、角闪石、石英、透闪石、方解石、黑云母、白云母、晶质石墨、磁铁矿等。岩石中变质矿物被压扁拉长,呈条带状、透镜状定向排列,石英具波状消光与其他片状矿物共同构成岩石鳞片粒状变晶结构,片状构造、片麻状构造。

3 典型矿床地质特征

敖包山晶质石墨矿集区主要分布于肃北县红柳峡—梧桐井一带,东西长近50 km,南北宽约10 km。目前,已发现晶质石墨矿床8个(图1b),矿床成因属区域变质形成。其中红柳峡晶质石墨矿、白台沟东晶质石墨矿、敖包山晶质石墨矿、大敖包沟晶质石墨矿已完成普查评价,现将其矿床地质特征简述如下:

3.1 红柳峡晶质石墨矿

矿区内出露地层主要为太古宙—古元古界敦煌岩群(ArPtD)。其中B岩组大面积出露于矿区中部(图2a),呈近东西向带状展布,为矿区主要含矿地层。区内地层受逆断层挤压,受变质分异花岗岩脉的影响,层间揉皱、挠曲及拉断等现象极为发育。

矿区共圈定晶质石墨矿体68条,矿体形态变化较大,呈透镜状、似层状、层状,长56~5068 m,厚2.01~11.84 m,固定碳含量2.03%~14.44%,矿体顶底板围岩均为二云石英片岩,局部为大理岩。该矿床评审备案晶质石墨矿物资源量246万t^②。

3.2 白台沟东晶质石墨矿

该矿床位于红柳峡晶质石墨矿的东延(图2b),二者无缝连接,其矿床地质特征完全一致。矿区共圈定晶质石墨矿体34条,长50~3440 m,厚2.0~17.46 m,固定碳含量2.06%~6.59%。该矿床评审备案晶质石墨矿物资源量255万t^③。

3.3 敖包山晶质石墨矿

矿区内出露地层主要为太古宙—古元古界敦煌岩群(ArPtD),分布于整个矿区,其中二云石英片岩是晶质石墨的赋矿层位(图2c)。矿区内构造形式复杂,构造变形强烈,褶皱、断裂较为发育。敖包山晶质石墨矿整体受复式向形构造控制。

矿区内共圈定晶质石墨矿体21条,各矿体之间相互平行分布,长100~1490m,厚2.00~51.11m,固定

碳含量在 2.46%~6.72%, 矿区固定碳平均品位 5.62%。矿体走向大致呈 106°, 倾角 45°~70°。该矿床评审备案晶质石墨矿物资源量 556 万 t^①。

3.4 大敖包沟晶质石墨矿

矿区出露地层为太古宇—古元古界敦煌岩群 (ArPtD), 该套地层分布于整个矿区, 晶质石墨赋存于二云石英片岩中(图 2d), 晶质石墨矿(带)体的空间分布严格受其控制。区内断裂及褶皱构造(图 3a、b)极为发育, 次生的挠曲、片理及片麻理较为常见。主要含矿层大致呈东西向展布, 整体受帚状向形构造控制。

矿区共圈定晶质石墨矿体 78 条, 长 200~4554 m, 厚 2.76~36.87 m, 固定碳平均品位 2.12%~4.81%。矿体呈层状、带状展布, 倾向南, 局部偏转为南西或南东, 倾角 40°~65°。该矿床评审备案晶

质石墨矿物资源量 657 万 t^②。

4 样品采集与分析方法

本次研究工作共采集样品 10 件, 其中 4 件样品来自敖包山晶质石墨矿(JQ9、JQ10 为黑云斜长片麻岩, JQ7、JQ8 为斜长角闪岩); 3 件样品来自红柳峡晶质石墨矿(JQ18、JQ19 为二云石英片岩, JQ20 为斜长角闪岩); 2 件样品来自大敖包沟晶质石墨矿(JQ14 为斜长角闪岩, JQ15 为二云石英片岩); 1 件样品来自白台沟东晶质石墨矿(JQ21 为斜长角闪岩)。

全岩主量元素和微量元素分析在核工业北京地质研究院分析测试研究中心完成。主量元素用 X 射线荧光光谱法(XRF)分析, 所用仪器为荷兰 FHLISP 公司 PW2404 顺序扫描型 X 射线荧光光谱仪。二价铁用湿化学滴定法测定。实验过程中温

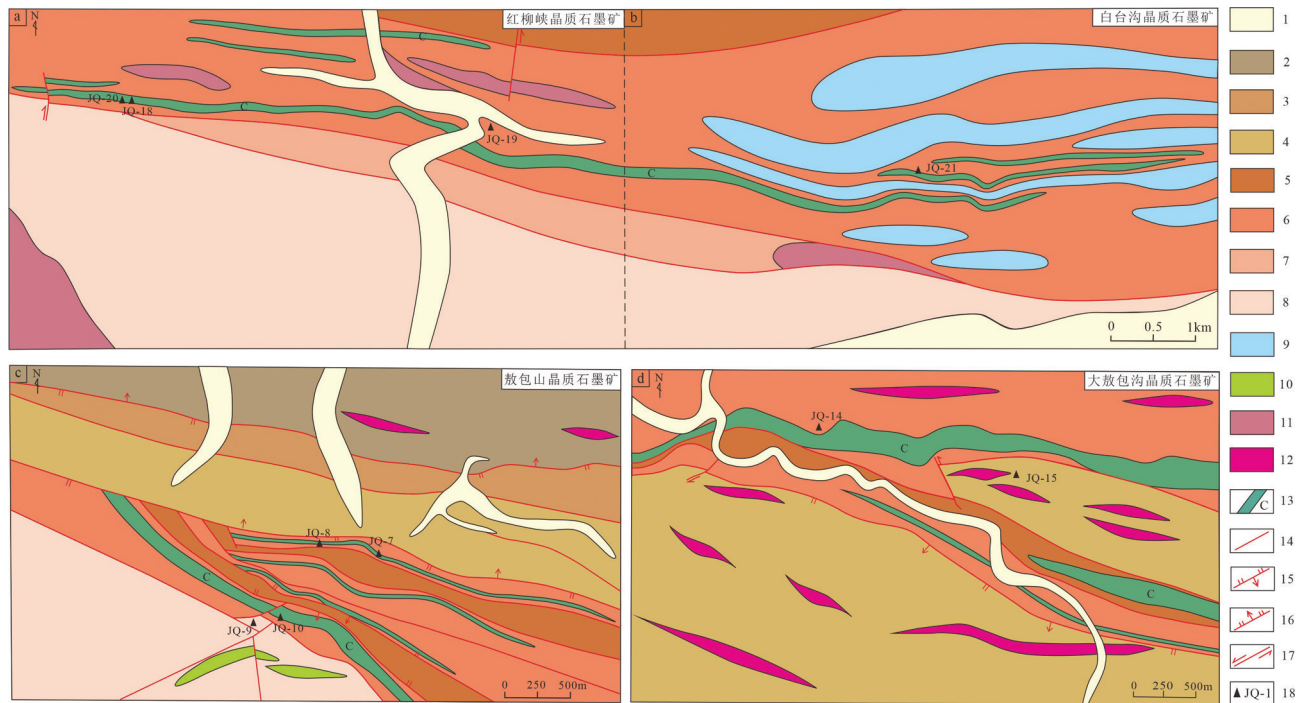


图2 敖包山矿集区晶质石墨矿床地质简图

1—第四系冲洪积; 2—敦煌岩群 C 岩组三岩段; 3—敦煌岩群 C 岩组二岩段; 4—敦煌岩群 C 岩组一岩段; 5—敦煌岩群 B 岩组三岩段; 6—敦煌岩群 B 岩组二岩段; 7—敦煌岩群 B 岩组一岩段; 8—敦煌岩群 A 岩组; 9—大理岩; 10—辉绿玢岩脉; 11—二长花岗岩脉; 12—花岗伟晶岩脉; 13—石墨矿化层; 14—实测性质不明断层及编号; 15—实测逆断层; 16—实测正断层; 17—实测平移断层; 18—样品采集位置及编号

Fig.2 The geological sketch map of crystalline graphite deposit in the Aobanshan deposit-concentrated area

1—Quaternary alluvial proluvial; 2—The third section of C-rock member of Dunhuang Group; 3—The second section of C-rock member of Dunhuang Group; 4—The first section of C-rock member of Dunhuang Group; 5—The third section of B-rock member of Dunhuang Group; 6—The second section of B-rock member of Dunhuang Group; 7—The first section of B-rock member of Dunhuang Group; 8—A-rock member of Dunhuang Group; 9—Marble; 10—Diabase porphyrite vein; 11—Monzogranite vein; 12—Granite pegmatite vein; 13—Graphite mineralized layer; 14—Measured unknown fault and number; 15—Measured reverse fault; 16—Measured normal fault; 17—Measured translational fault; 18—Sample location and number

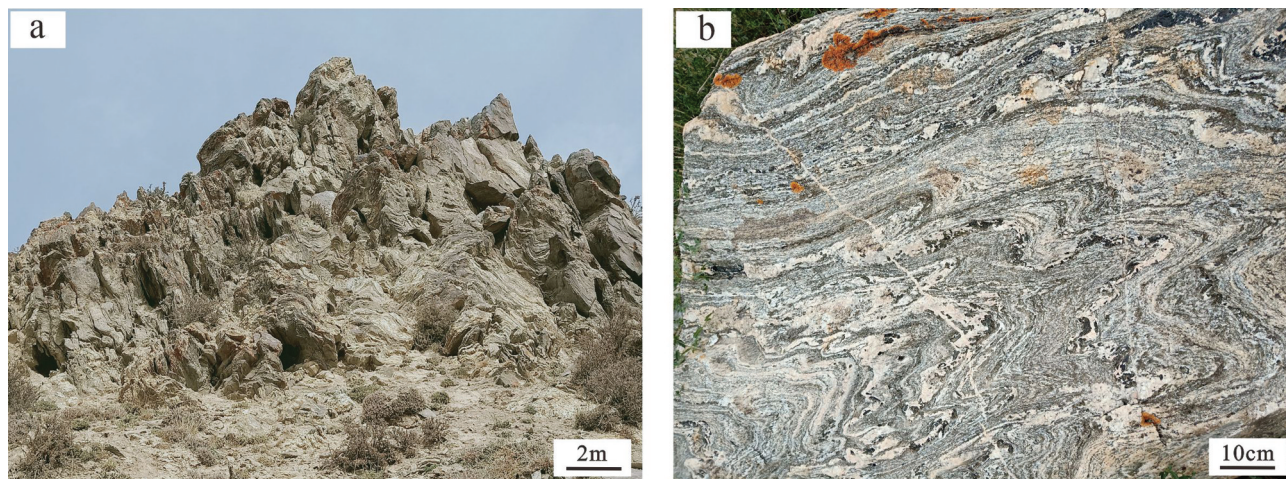


图3 大敖包沟晶质石墨矿含矿地层褶皱变形特征

Fig.3 Characteristics of fold deformation in ore-bearing strata of the Daaobaogou crystalline graphite deposit

度 20℃和相对湿度 30%，主量元素的分析精度为 1%~5%。微量元素分析通过电感耦合等离子体质谱(ICP-MS)分析，测试仪器型号为 Finnigan MAT 制造的 HR-ICP-MS (Element 1) 型 ICP-MS，大多数微量元素的分析精度优于 5%。

5 岩相学特征

敖包山晶质石墨矿集区变质岩主要为二云石英片岩、黑云斜长片麻岩、斜长角闪岩等。

二云石英片岩：浅灰色，鳞片粒状变晶结构，片状构造。矿物组成主要为石英(50%±)、斜长石(10%±)、黑云母(16%±)、白云母(15%±)、晶质石墨(7%±)等。黑云母呈片状，片径多在 0.08 mm×0.3 mm~0.2 mm×0.7mm，整体具定向分布；白云母呈片状，一般和黑云母相对聚集状定向不均匀分布，片径和黑云母相近；斜长石呈近等轴粒状，大多数和云母定向分布，粒径大多在 0.3~0.6 mm；石英呈他形粒状，透明洁净，粒径大多在 0.2~0.5 mm；晶质石墨呈片状、长条状较均匀分布，多数被包裹或半嵌于石英和云母中，往往与不透明铁质矿物、炭质不规则集合体等混杂或连体，半定向散布，石墨片径为 0.05 mm×0.1 mm~0.15 mm×0.3 mm(图 4c, d)。

黑云斜长片麻岩：呈浅灰色，鳞片粒状变晶结构，片麻状构造。主要组成矿物为石英(20%±)、斜长石(53%±)、黑云母(20%±)及少量角闪石(5%±)等。黑云母呈鳞片状集合体，片径多在 0.08 mm×0.2 mm~0.2 mm×0.8mm；斜长石呈半自形板柱状，

粒径 3 mm±；石英多呈他形粒状，粒径 2~3 mm，普遍具压扁拉长现象(图 4e)。

斜长角闪岩：灰黑色，粒柱状变晶结构，块状构造，局部矿物定向排列明显，具片麻状构造。主要由角闪石(60%±)和斜长石(37%±)组成，局部含有少量石榴石。斜长石多呈半自形板柱状，粒径 2~5 mm；角闪石呈短柱状，粒径 4 mm±；石榴石呈半自形粒状，粒径一般 1~4 mm(图 4f)。

6 岩石地球化学特征及原岩恢复

6.1 主量元素特征

敖包山晶质石墨矿集区二云石英片岩、黑云斜长片麻岩和斜长角闪岩的主微量元素分析结果见表 1。斜长角闪岩 SiO₂ 变化范围为 49.67%~52.62%，平均为 50.64%；Al₂O₃ 变化范围为 13.25%~15.25%，平均为 14.19%；二云石英片岩 SiO₂ 变化范围为 58.90%~62.53%，平均为 60.49%；Al₂O₃ 变化范围为 15.20%~17.39%，平均为 16.36%；黑云斜长片麻岩 SiO₂ 变化范围为 67.30%~70.36%，平均为 68.83%；Al₂O₃ 变化范围为 15.48%~17.03%，平均为 16.24%。黑云斜长片麻岩具有最高的 MgO 含量，其次为斜长角闪岩，二云石英片岩 MgO 含量最低。从斜长角闪岩、二云石英片岩到黑云斜长片麻岩片麻岩，SiO₂ 含量逐渐增加，FeO、CaO 和 Na₂O 含量逐渐增加，Al₂O₃ 含量与 K₂O 含量逐渐增加(图 5)。斜长角闪岩 A/CNK 变化范围为 0.56~0.72，均小于 1；二云石英片岩和黑云斜长片麻岩的 A/CNK 值较高，变

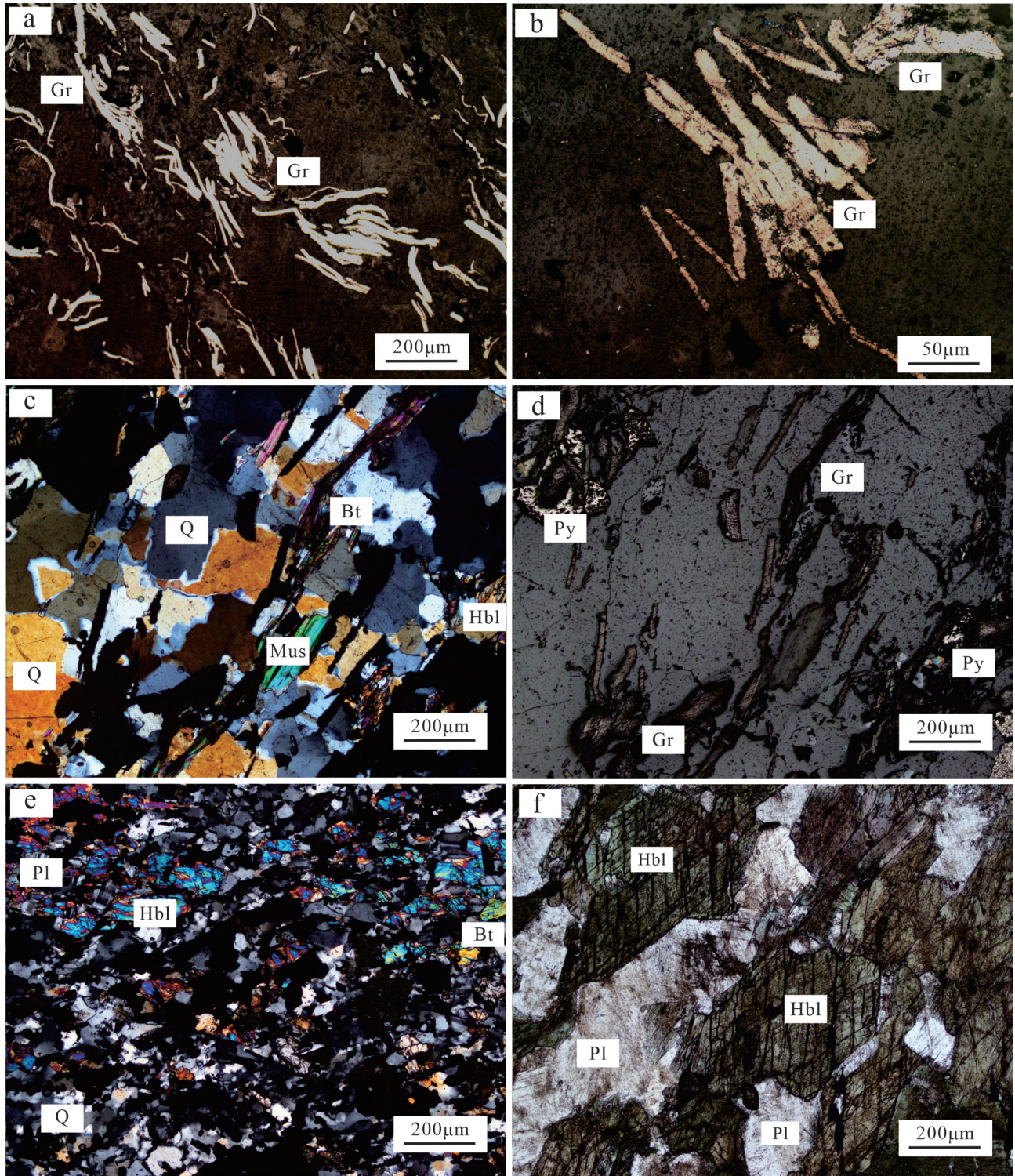


图4 敖包山晶质石墨矿集区变质岩显微照片

a、b、d—含石墨二云石英片岩；c—二云石英片岩；e—黑云斜长片麻岩；f—斜长角闪岩；
Bt—黑云母；Gr—晶质石墨；Hbl—角闪石；Mus—白云母；Pl—斜长石；Py—黄铁矿；Q—石英

Fig.4 Micrographs of metamorphic rocks of the Aobaoshan crystalline graphite deposit area

a, b, d—Graphite-bearing two-mica quartz schist; c—Two-mica quartz schist; e—Biotite plagioclase gneiss; f—Plagioclase amphibolite; Bt—Biotite; Gr—Crystalline graphite; Hbl—Hornblende; Mus—Muscovite; Pl—Plagioclase; Py—Pyrite; Q—Quartz

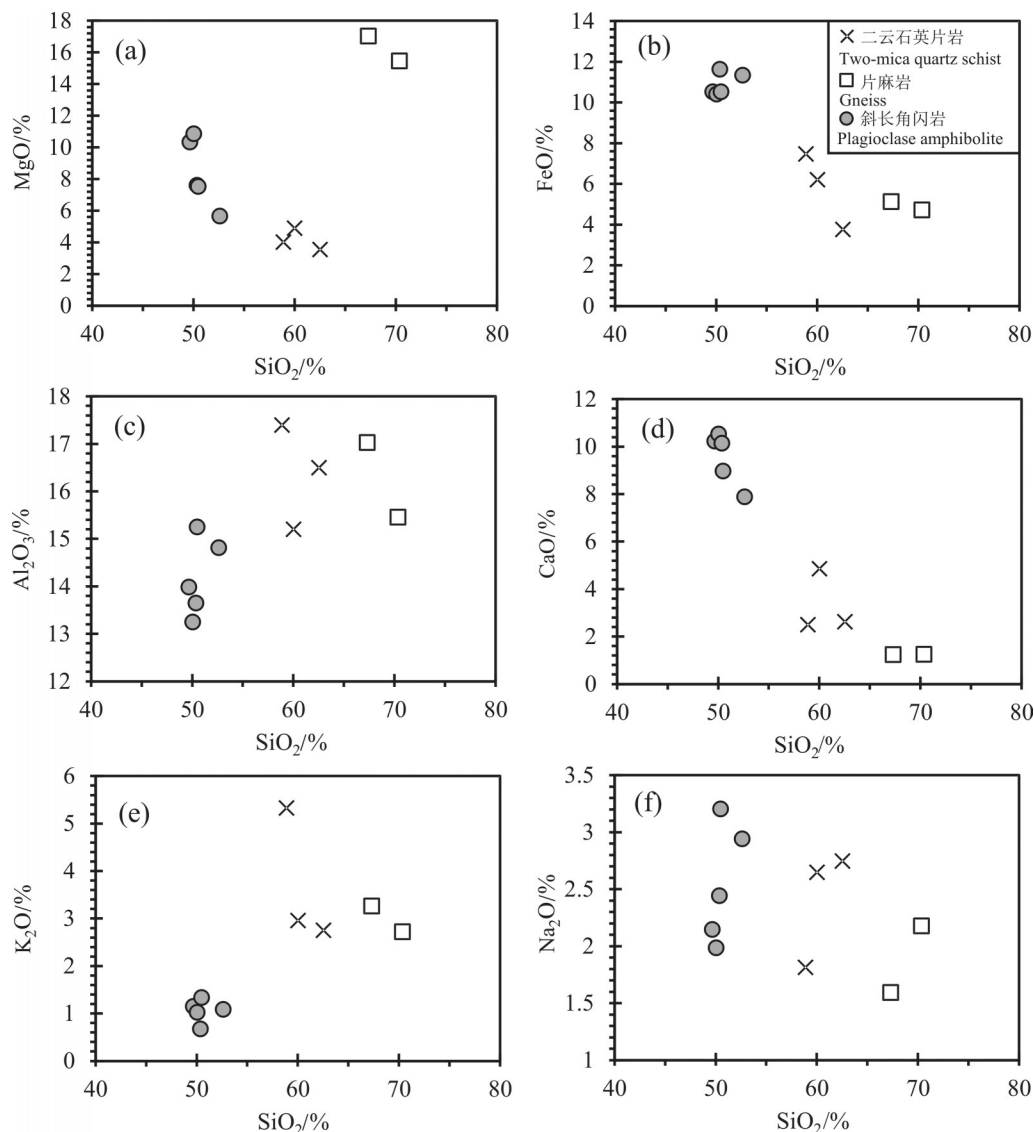


图5 主量元素的相关图解

Fig.5 The diagrams of major elements

化范围分别为0.93~1.35和1.76~2.03。斜长角闪岩MgO/CaO变化范围为0.72~1.03,平均值为0.89;二云石英片岩和黑云斜长片麻岩的MgO/CaO值较高,变化范围分别为1.01~1.60和0.98~1.26。斜长角闪岩K₂O/Na₂O平均比值为0.42;二云石英片岩和黑云斜长片麻岩K₂O/Na₂O平均比值分别为1.68和1.65。斜长角闪岩、二云石英片岩和黑云斜长片麻岩SiO₂/Al₂O₃平均比值为分别为3.58、3.71和4.25。

6.2 微量元素特征

微量元素原始地幔标准化蛛网图显示二云石英片岩和黑云斜长片麻岩具有相似的元素富集和

亏损特征,呈现大离子亲石元素Rb、K等的富集, Ba、Nb、Ta、Zr、Hf、Ti、Sr等元素的亏损;斜长角闪岩具有弱的Nb、Ta亏损和强烈的Zr、Hf亏损(图6a)。斜长角闪岩 Σ REE为(31.28~145.81) $\times 10^{-6}$,平均值为68.50 $\times 10^{-6}$;二云石英片岩 Σ REE为(87.91~276.32) $\times 10^{-6}$,平均值为211.15 $\times 10^{-6}$;片麻岩 Σ REE为(214.08~270.64) $\times 10^{-6}$,平均值为242.36 $\times 10^{-6}$ 。从斜长角闪岩、二云石英片岩到黑云斜长片麻岩, Σ REE增高。稀土元素球粒陨石标准化图解显示二云石英片岩、黑云斜长片麻岩和斜长角闪岩具有轻稀土富集的特征。除一个样品外,其余二云石英片

表1 敖包山晶质石墨矿集区岩石化学分析结果

Table 1 Petrochemical analyses of Aobaoshan crystalline graphite deposit—concentrated area

样品编号	JQ-15	JQ-18	JQ-19	JQ-9	JQ-10	JQ-7	JQ-8	JQ-14	JQ-20	JQ-21
样品岩性	二云石英片岩			黑云斜长片麻岩			斜长角闪岩			
矿区	大敖包沟	红柳峡	红柳峡	敖包山	敖包山	敖包山	敖包山	大敖包沟	红柳峡	白台沟东
SiO ₂	60.78	57.82	56.82	65.06	68.55	48.39	48.67	49.28	48.07	50.79
TiO ₂	0.818	0.875	0.764	1.01	0.916	0.692	0.717	1.29	1.11	1.5
Al ₂ O ₃	16.03	14.64	16.78	16.46	15.06	13.62	12.88	13.35	14.52	14.3
Fe ₂ O ₃	0.89	0.45	1.54	1.58	0.93	0.93	0.84	1.80	1.19	1.64
FeO	7.11	7.5	7.04	4.95	4.6	10.25	10.12	11.38	10.02	10.94
MnO	0.114	0.133	0.111	0.105	0.11	0.237	0.233	0.224	0.176	0.181
MgO	3.44	4.7	3.86	1.51	1.19	10.06	10.55	7.43	7.16	5.45
CaO	2.54	4.67	2.41	1.2	1.21	9.96	10.24	9.92	8.54	7.61
Na ₂ O	2.67	2.55	1.75	1.54	2.12	2.09	1.93	2.39	3.05	2.84
K ₂ O	2.67	2.85	5.14	3.15	2.65	1.12	0.993	0.659	1.27	1.05
P ₂ O ₅	0.12	0.126	0.247	0.1	0.09	0.064	0.062	0.112	0.111	0.227
LOI	1.46	2.35	2.16	2.34	1.52	0.9	1.1	0.38	3.14	1.8
Total	98.65	98.66	98.62	99.01	98.95	98.31	98.34	98.22	98.36	98.33
A/CNK	1.35	0.93	1.31	2.02	1.76	0.60	0.56	0.59	0.66	0.73
A/NK	0.05	0.05	0.08	0.09	0.06	0.06	0.06	0.05	0.04	0.04
Rb	134	85.7	187	135	111	13.5	13.3	8.33	37.3	27.1
Sr	166	259	187	128	152	139	151	136	194	339
Ba	486	1337	1333	734	1023	220	209	132	318	408
Zr	76.4	31.1	24.9	77.9	58.5	6.80	6.71	11.9	14.6	8.07
Hf	2.55	1.09	0.759	2.59	1.97	0.356	0.419	0.588	0.992	0.524
Th	12.9	22.1	13.5	17.3	18	0.972	1.12	0.431	2.55	2.88
U	2.27	1.57	1.74	2.84	2.69	0.264	0.299	0.24	0.689	0.628
Y	18.4	17.9	19.7	33.6	31.4	15.7	17.4	26.2	18.6	26.4
Nb	21.6	9.83	11.7	18.5	16.5	2.80	2.99	3.88	7.29	13.2
Ta	1.41	0.402	0.505	1.23	1.07	0.182	0.207	0.258	0.432	0.733
Cr	68.5	72.9	53.6	84	73.9	254	321	262	49.7	50.4
Ni	29.2	40.1	30	26.4	25.6	126	142	116	83.7	55.8
Co	15.8	26.9	24.3	15.5	14.8	52.5	53.8	63	48.7	42.8
Sc	18.3	19.3	17.3	17.7	15.7	43.8	50.3	48.1	34.3	32.3
Ga	21.7	18.1	22.6	20.9	18.8	14.0	13.4	18.1	19.6	19.4
La	14.5	60.9	65	37.9	51.4	4.08	5.19	5.22	13.9	28.7
Ce	36.5	124	114	89.4	116	9.21	11.1	11.5	30.6	56.9
Pr	3.73	14.4	13.4	10.5	13.3	1.32	1.55	1.97	3.78	6.51
Nd	16.3	51.6	50.9	40.9	53.3	6.28	7.17	9.71	16.0	28.3
Sm	3.47	7.96	7.78	8.74	10.8	1.89	1.98	2.80	3.64	5.52
Eu	1.20	1.15	1.49	1.59	1.73	0.63	0.694	1.23	1.18	1.58
Gd	2.56	5.82	5.99	7.19	7.60	1.83	1.95	3.24	3.15	4.86
Tb	0.493	0.887	0.98	1.23	1.30	0.414	0.448	0.724	0.613	0.946
Dy	3.49	4.41	4.49	6.81	6.83	2.32	2.73	4.09	3.66	4.93
Ho	0.703	0.672	0.687	1.23	1.29	0.52	0.551	0.936	0.746	0.981
Er	2.04	2.13	2.04	3.26	3.14	1.26	1.41	2.55	1.96	2.87
Tm	0.36	0.299	0.315	0.657	0.581	0.301	0.29	0.446	0.33	0.455
Yb	2.22	1.81	1.87	4.00	2.72	0.947	1.10	2.31	1.97	2.85
Lu	0.346	0.279	0.264	0.668	0.651	0.276	0.297	0.386	0.288	0.411
La	14.5	60.9	65	37.9	51.4	4.08	5.19	5.22	13.9	28.7
Ce	36.5	124	114	89.4	116	9.21	11.1	11.5	30.6	56.9
Pr	3.73	14.4	13.4	10.5	13.3	1.32	1.55	1.97	3.78	6.51
Nd	16.3	51.6	50.9	40.9	53.3	6.28	7.17	9.71	16.0	28.3
Sm	3.47	7.96	7.78	8.74	10.8	1.89	1.98	2.80	3.64	5.52
Eu	1.20	1.15	1.49	1.59	1.73	0.63	0.694	1.23	1.18	1.58
Gd	2.56	5.82	5.99	7.19	7.60	1.83	1.95	3.24	3.15	4.86
Tb	0.493	0.887	0.98	1.23	1.30	0.414	0.448	0.724	0.613	0.946
Dy	3.49	4.41	4.49	6.81	6.83	2.32	2.73	4.09	3.66	4.93
Ho	0.703	0.672	0.687	1.23	1.29	0.52	0.551	0.936	0.746	0.981
Er	2.04	2.13	2.04	3.26	3.14	1.26	1.41	2.55	1.96	2.87
Tm	0.36	0.299	0.315	0.657	0.581	0.301	0.29	0.446	0.33	0.455
Yb	2.22	1.81	1.87	4.00	2.72	0.947	1.10	2.31	1.97	2.85
Lu	0.346	0.279	0.264	0.668	0.651	0.276	0.297	0.386	0.288	0.411
LREE/HREE	6.20	15.94	15.18	7.55	10.22	2.98	3.15	2.21	5.43	6.97
ΣREE	87.91	276.32	269.21	214.08	270.64	31.28	36.46	47.11	81.82	145.81
La/Yb	3.47	7.96	7.78	8.74	10.8	1.89	1.98	2.80	3.64	5.52
Rb/Sr	0.81	0.33	1.00	1.05	0.73	0.10	0.09	0.06	0.19	0.08
Sr/Ba	0.34	0.19	0.14	0.17	0.15	0.63	0.72	1.03	0.61	0.83
Th/U	5.68	14.08	7.76	6.09	6.69	3.68	3.75	1.80	3.70	4.59
V/Cr	2.01	2.00	2.61	1.50	1.23	0.94	0.85	1.34	5.59	5.79

注:表中主量元素分析结果(%);微量元素分析结果(10⁻⁶)。

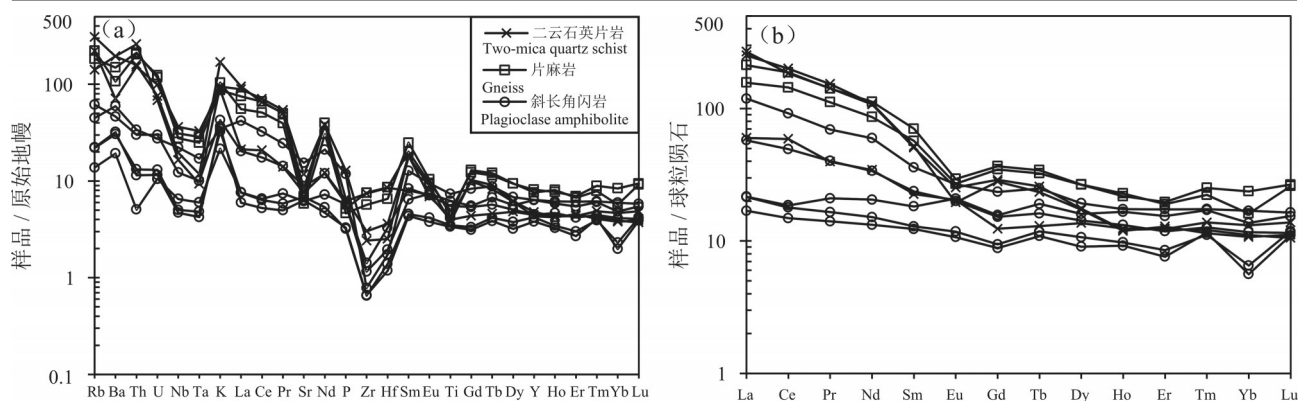


图6 敖包山晶质石墨矿集区样品的原始地幔标准化图解(a)和球粒陨石标准化图解(b)(原始地幔和球粒陨石标准化值来自Palme and O'Neill, 2014)

Fig.6 Primitive mantle-normalized trace element patterns (a) and Chondrite-normalized REE patterns (b) of the samples from the Aobaoshan crystalline graphite deposit concentrated area (Normalized values for primitive mantle and chondrites from Palme and O'Neill, 2014)

岩和黑云斜长片麻岩样品均具有明显的Eu负异常, δEu 平均值分别为0.77和0.57;斜长角闪岩具有弱的Eu正异常, δEu 平均值为1.06,重稀土元素具有平坦的配分模式,三样品存在Yb负异常(图6b)。斜长角闪岩LREE/HREE=2.21~6.97,轻重稀土元素分馏程度较弱;二云石英片岩和黑云片麻岩LREE/HREE平均值为12.44和8.89,轻重稀土元素分异较强烈(杨镇熙等,2021)。

6.3 原岩恢复

研究区敦煌岩群主要岩性有二云石英片岩、白云母石英片岩、黑云斜长片麻岩、斜长角闪岩、大理岩等,整体表现为一套层状无序的岩石组合特征,面状构造极为发育,产状类型复杂多样,没有原始沉积过程中残存的沉积构造,呈假层状产出,总体序次关系混乱,后期改造、叠加、置换强烈。

在进行变质岩原岩恢复时,根据研究区地质产状、岩石共生组合及其相互(接触)关系和岩相学标志无法得到正确的结果,须借助岩石化学成分和地球化学上的某些差异,来分析它们的原岩性质。这是由于变质岩的岩石化学及地球化学特征,基本上能反映原岩的物化特征,并主要受原岩形成作用特点的制约。在进行原岩恢复时,除了采用主量元素含量直接对比外,一些岩石化学参数以及由这些参数构建的岩石地球化学图解均可用于变质岩的识别(王仁民等,1987;赵吉昌等,2016)。

由于Zr、Ti和Ni为不相容或耐熔元素,活动性弱,变质过程中不易发生变化,其比值基本不发生

变化或变化范围较小,而且在Ni含量相同的情况下,沉积岩比火成岩具有较高的Zr/TiO₂。因此,利用这三种相对不活泼元素建立的Zr/TiO₂-Ni图解能比较准确地地区分正变质岩和副变质岩(Winchester et al., 1980)。图7a中显示二云石英片岩和黑云斜长片麻岩投点落入了沉积岩区,指示样品为副变质岩;斜长角闪岩样品投点落入了火成岩区,指示样品为正变质岩。二云石英片岩和黑云斜长片麻岩高钾贫钠的特点与沉积岩的特点相一致;而斜长角闪岩高钠贫钾的特点与火成岩的特点相一致。

Ga/Sc值可以反映火成岩岩浆分异程度,Nb/Y值则只受碱度影响而与火成岩分异作用无关,因此可作为碱度指标(赵振华,2016)。在火山岩Ga/Sc-Nb/Y判别图解中,斜长角闪岩样品投点落入了亚碱性玄武岩的范围内(图7b),指示斜长角闪岩原岩为亚碱性基性岩(Winchester and Floyd, 1977)。斜长角闪岩无Sr和Eu负异常,表明样品中存在斜长石的堆晶作用或者源区无斜长石的残留。与王忠梅等(2013)对红柳峡石榴石斜长角闪岩的原岩类型认识一致。

Simonen图解的适用范围比较广泛,在恢复变质岩原岩类型上效果较好,投图结果显示二云石英片岩投点落入了泥质沉积岩的范围内,黑云斜长片麻岩则落入了泥质沉积岩和砂质沉积岩的分界线上,斜长角闪岩落入了火山岩的范围内(图7c)。

稀土元素由于化学稳定性好,不易受交代作用的

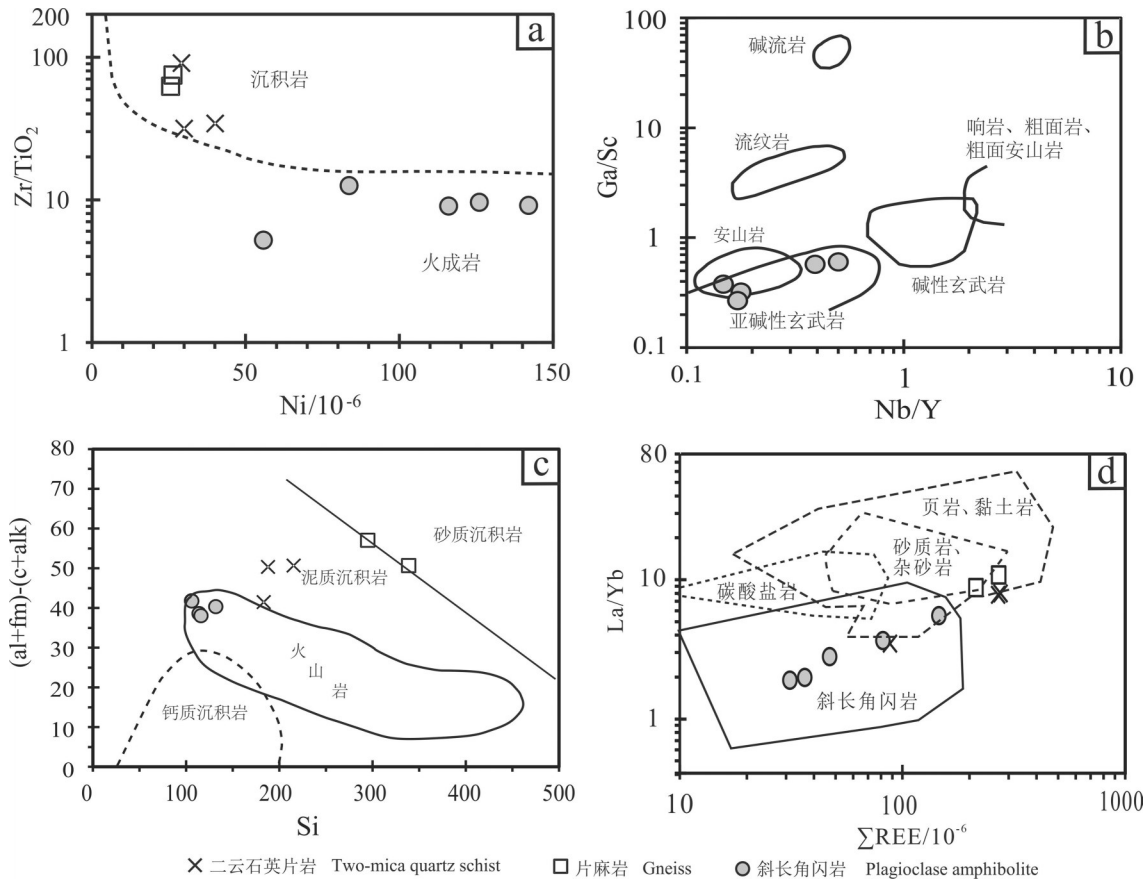


图7 Zr/TiO₂-Ni图解(a, 底图据 Winchester et al., 1980); Ga/Sc-Nb/Y图解(b, 底图据 Winchester and Floyd, 1977); (al+fm)-(c+alk)-Si图解(c, 底图据 Simonen, 1953); La/Yb-ΣREE图解(d, 底图据王仁民等, 1987)

Fig.7 The diagram of Zr/TiO₂ vs. Ni (a, modified from Winchester et al., 1980); The diagram of Ga/Sc vs. Nb/Y (b, modified from Winchester and Floyd, 1977); The diagram of (al+fm)-(c+alk) vs. Si (c, modified from Simonen, 1953); The diagram of La/Yb vs. ΣREE (d, modified from Wang Renmin et al., 1987)

影响,常用于变质岩原岩的恢复。在La/Yb-ΣREE图解中,二云石英片岩和黑云斜长片麻岩落入了页岩和黏土岩区,斜长角闪岩样品则落入了斜长角闪岩区(图7d)。

在上述图解的基础上,结合岩相学分析结果,认为敖包山晶质石墨矿集区变质岩原岩是一套以含页岩、黏土岩和基性岩为主,夹杂少量砂质沉积岩的岩石组合,表明其形成于浅水区,水动力作用较弱,可能与陆源碎屑河流和边缘海沉积环境有关。

7 古构造环境探讨

不同构造背景下形成的岩石,其矿物成分和赋存于岩石中的某些元素含量及其比值等地球化学参数存在差异,利用这些差异特征能较好地反映其形成时的构造环境(杨培奇等, 2017; 邓绍军等,

2020)。

研究区敦煌岩群表壳岩系是一套形成于活动大陆边缘滨-浅海环境的碎屑岩-泥质岩-泥灰岩-碳酸盐岩建造,沉积时代为太古宙-古元古代,之后经历了古元古代晚期角闪岩相-麻粒岩相变质作用,并受到中元古代早期和古生代岩浆-变质作用改造(Wang et al., 2014; Zhao et al., 2019)。其中二云石英片岩和黑云斜长片麻岩的原岩为页岩、黏土岩,夹杂少量砂质沉积岩,反映水动力作用较弱。利用微量元素比值可以判别古氧化还原条件,Ni/Co比值大于7.00、V/Cr比值大于4.25和U/Th比值大于1.25为厌氧环境,Ni/Co比值变化范围5.00~7.00、V/Cr比值变化范围2.00~4.25、U/Th比值变化范围0.75~1.25为贫氧环境,Ni/Co比值小于5.00、V/Cr比值小于2.00、U/Th比值小于0.75为富氧环境(Jones

and Manning, 1994)。判别时不能仅依靠单个指标,需结合多个指标进行综合判识(周炼等,2011;杨季华等,2020)。二云石英片岩 $V/Cr=2.00\sim 2.61$, $Ni/Co=1.23\sim 1.85$, $U/Th=0.07\sim 0.18$;黑云斜长片麻岩 $V/Cr=1.23\sim 1.50$, $Ni/Co=1.70\sim 1.73$, $U/Th=0.15\sim 0.16$ 。指示原岩沉积环境为氧化环境。元素U和Th同样对氧化还原环境敏感,Wignall(1994)考虑自生铀的相对含量而建立了 $\delta U=2U/(Th/3+U)$ 关系式,当 $\delta U>1$ 表示还原环境, $\delta U<1$ 表示氧化环境。二云石英片岩 $\delta U=0.35\sim 0.69$;黑云斜长片麻岩 $\delta U=0.62\sim 0.66$,同样指示氧化环境。

Ba、Sr、Ni等元素含量对水体盐度的变化具有较好的指示作用(杨季华等,2020)。Sr与Ba化学性质相似,但是在溶液中Sr的迁移能力比Ba强,当水体盐度增大时,Sr/Ba比值会持续增大。当 $Sr/Ba>1.0$ 时为海相沉积; Sr/Ba 变化范围为 $0.6\sim 1.0$ 时,为半咸水相;当 $Sr/Ba<0.6$ 时为陆相沉积(王益友等,1979)。在Sr-Ba图解中(王仁民等,1987),二云石英片岩和黑云斜长片麻岩均落入了半咸水相(图8),为海陆交互相。利用Ni含量同样可以判断水体盐度。海洋沉积物中的Ni含量高于淡水沉积物中的Ni含量,通常Ni含量大于 40×10^{-6} 为咸水环境沉积, $20\times 10^{-6}\sim 25\times 10^{-6}$ 时为淡水环境沉积, $25\times 10^{-6}\sim$

40×10^{-6} 为半咸水沉积(邓宏文和钱凯,1993;田景春和张翔,2016)。二云石英片岩和黑云斜长片麻岩的Ni含量变化范围分别为 $29.2\times 10^{-6}\sim 40.1\times 10^{-6}$ 和 $25.6\times 10^{-6}\sim 26.4\times 10^{-6}$,同样可判断为半咸水相。

利用 $(Al_2O_3+TiO_2)-(SiO_2+K_2O)-\Sigma$ 其余组分(Σ 其余组分= $100-Al_2O_3-TiO_2-SiO_2-K_2O$)图解可以判断黏土岩形成时的古地理和古气候环境(王仁民等,1987)。图9中样品落入了干燥气候带的海相、湖相和泻湖相黏土区以及寒冷和中等寒冷气候带的陆相黏土成分的重叠区。

斜长角闪岩微量元素特征显示出有弱的Nb、Ta亏损和强烈的Zr、Hf亏损,与岛弧玄武岩的微量元素特征比较相似,明显不同于OIB和MORB的特征,表明斜长角闪岩的原岩形成于岛弧环境(Li et al., 2015)。利用 SiO_2-K_2O/Na_2O 和 $SiO_2/Al_2O_3-K_2O/Na_2O$ 图解可以判别构造环境,斜长角闪岩落入了岛弧环境,二云石英片岩和黑云斜长片麻岩几乎全部落入活动大陆边缘区域(图10)。与王忠梅等(2013)对红柳峡石榴石斜长角闪岩的构造环境认识一致,表明敦煌地块在古元古代末期为岛弧构造环境。与刘祥(2019)对敦煌地块的三危山、旱峡和红柳峡出露的变质岩构造环境认识一致,活动大陆边缘构造环境可能与敦煌地块和北山地块之间的大洋向南俯冲有关。

综上所述,敖包山晶质石墨矿集区二云石英片岩和黑云斜长片麻岩形成的构造环境为活动大陆边缘,古沉积环境为干燥气候带条件下富氧的海陆交互相;古水体介质主要为盐度较高的半咸水;斜长角闪岩形成于岛弧环境。

8 结 论

本文在对敖包山晶质石墨矿集区矿床地质特征论述的基础上,采用岩相学、岩石地球化学方法恢复了敖包山晶质石墨矿集区变质岩的原岩类型,并探讨了其古构造环境,得出以下结论:

(1)敖包山晶质石墨矿集区晶质石墨矿床集中分布于太古宇—古元古界敦煌岩群地层中,晶质石墨主要赋存于二云石英片岩中,石墨呈显微鳞片—鳞片状分布于脉石矿物颗粒之间,晶质石墨矿成因为区域变质形成。

(2)敖包山晶质石墨矿集区二云石英片岩和黑

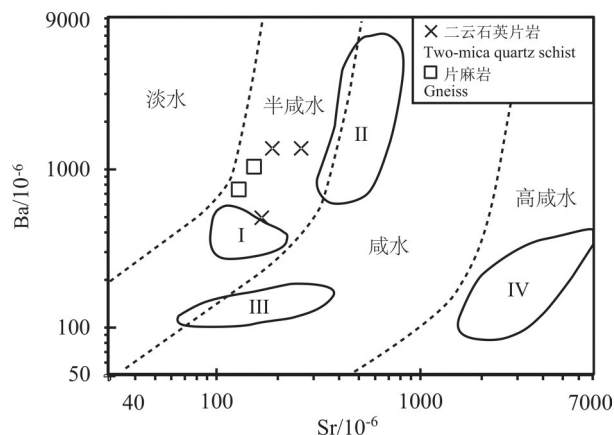


图8 Ba-Sr图解(底图据王仁民等,1987)

I—现代三角洲半咸水黏土区; II—太平洋远海相沉积物; III—俄罗斯地台不同年代海相碳酸盐区; IV—现代高咸水沉积物

Fig.8 The diagram of Ba versus Sr (modified from Wang Renmin et al., 1987)

I—Modern delta brackish water clay area; II—Pacific pelagic sediments; III—Marine carbonate area of Russian platform in different ages; IV—Modern high salt water sediments

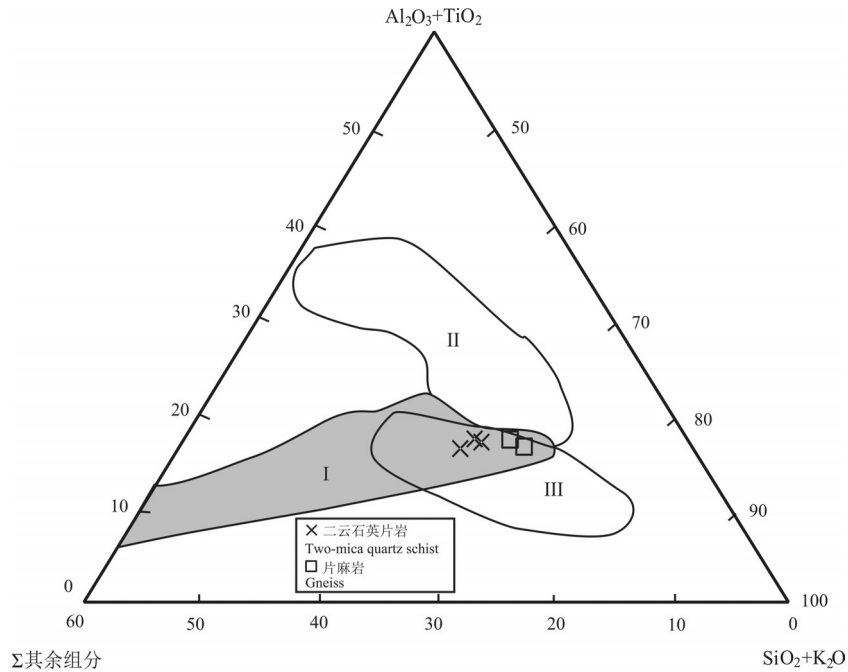


图9 不同气候带黏土岩的成分图解(底图据王仁民等, 1987)

I—干燥气候带的海相、湖相和泻湖相黏土成分区; II—潮湿和炎热气候带的陆相黏土成分区; III—寒冷和中等寒冷气候带的陆相黏土成分区

Fig.9 Composition diagram of clay rocks in different climatic zones (modified from Wang Renmin et al., 1987)

I—Marine, lacustrine and lagoonal clay in dry climate zone; II—Continental clay in humid and hot climate zone; III—Continental clay in cold and moderate cold climate zone

云斜长片麻岩的原岩为页岩、黏土岩;斜长角闪岩的原岩为亚碱性基性火山岩。

(3)敖包山晶质石墨矿集区变质岩原岩是一套以含页岩、黏土岩和基性火山岩为主,夹杂少量砂质沉积岩的岩石组合,表明其形成于浅水区,水动力环境较弱。

(4)二云石英片岩和黑云斜长片麻岩形成的构

造环境为活动大陆边缘,古沉积环境为干燥气候带条件下富氧的海陆交互相;古水体介质主要为盐度较高的半咸水;斜长角闪岩形成于岛弧环境。

注释

①甘肃省地质矿产勘查开发局第四地质矿产勘查院. 2019. 甘肃省肃北县敖包山晶质石墨矿普查报告[R].

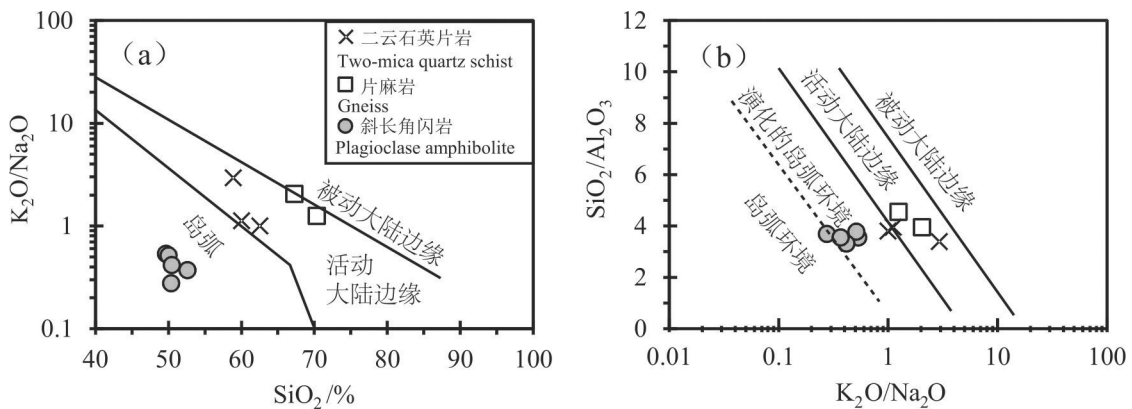


图10 SiO₂-K₂O/Na₂O(a)和 SiO₂/Al₂O₃-K₂O/Na₂O(b)图解(底图据 Roser and Korsch, 1986)

Fig.10 The plots of K₂O/Na₂O vs. SiO₂ (a) and SiO₂/Al₂O₃ vs. K₂O/Na₂O (b) (modified from Roser and Korsch, 1986)

- ② 甘肃省地质矿产勘查开发局第四地质矿产勘查院. 2020. 甘肃省肃北县红柳峡晶质石墨矿普查报告[R].
- ③ 甘肃省地质矿产勘查开发局第四地质矿产勘查院. 2020. 甘肃省肃北县白台沟东晶质石墨矿普查报告[R].
- ④ 甘肃省地质矿产勘查开发局第四地质矿产勘查院. 2021. 甘肃省肃北县大敖包沟晶质石墨矿普查报告[R].

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