金属矿产

剪切应变异常带近等距控矿模式——以粤西河台金矿为例

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[摘 要] 本文研究了河台金矿富矿体的分布规律并对河台金矿与富矿体有关的热液成矿期进行了构造-流体成矿数值模拟研究。研究表明,河台金矿的富矿体在平面上表现为左阶近等距的分布规律;剖面上也表现为近等距的分布规律,并都有北东向侧伏的规律。其中,据统计,河台金矿云西矿床相邻品位富集中心在侧伏方向上的距离为85~179m;河台金矿高村矿床相邻品位富集中心在侧伏方向上的距离为62~302m。剪切应变异常带是有利于发生剪切滑动与成矿的扩容区,且本区数值模拟产生的平面剪切应变异常带具有与富矿体分布特征一致的左阶近等距性。由此提出,剪切滑动之前剪切应变异常带的近等距性决定了剪切滑动后矿体的近等距性。以上控矿模式称为剪应变异常带近等距控矿模式。剪切应变异常带对矿体的控制可能形成于剪切应变异常带形成期的剪切滑动控矿及剪切应变异常带形成之后的微裂隙扩张控矿。将该模式控制的近等距性的矿体进行矿体统计分析预测,有望实现一定的找矿效果。

[关键词] 河台金矿 糜棱岩 近等距 控矿模式 剪切应变
[中图分类号] P588.121+597.3 [文献标识码] A [文章编号] 0495-5331(2014)03-0454-10
DOI:10.13712/j.cnki.dzykt.2014.03.006

Zhu Jiang-jian, Lin Ge, Zeng Qiao-song, Chen Guang-hao, Wang Jing-bin. A nearly equidistant ore-controlling model for shear-strain anomaly belts: An example of the Hetai gold deposit in western Guangdong Province [J]. Geology and Exploration, 2014, 50(3):0454-0463.

河台金矿是一个典型的与韧性剪切带有关的金矿床,也是目前粤西、桂东南已发现的最大的金矿床。关于河台金矿的成矿模式(叶锦华等,1993;欧阳玉飞等,2005,2007)、构造控矿规律(李新福等,2007)等,前人已开展了一些有益的探讨。已发现的含矿糜棱岩化带(9、11、12、13号糜棱岩化带)及富矿体在平面上具有左阶近等距分布的规律(王斯亮等,2000;朱江建等,2011a),且在剖面上也表现为一定的近等距性(王斯亮等,2000;伍思洪,2005)。然而,富矿体的近等距性至今尚未开展形成机制方面的研究。本文进一步统计了河台金矿金矿体的分布规律,并对河台金矿糜棱岩化之后的热液成矿期进行了平面数值模拟研究,以期对以上问题进行有益探讨。

1 河台金矿矿床地质特征

河台金矿位于云开大山变质杂岩体北部、罗定-广宁断裂变质带和吴川-四会断裂变质带的交汇部位(图1)。该矿北部出露震旦系局部混合岩化的石英云母片岩、石英岩等,其中混合岩的锆石SHRIMP U-Pb年龄为239.6Ma(翟伟等,2006)。南部出露奥陶系薄层浅变质砂岩、粉砂岩及薄层板岩,其通过F_1断裂与震旦系呈断层接触。F_1断裂是矿区主要的导矿构造之一,位于矿区南部,倾向北西,倾角55°~70°(李新福等,2007)。含矿构造为糜棱岩化带及发育于其中的脆性断裂。导矿构造与含矿构造在剖面上为"y"字型展布(图1)。赋金矿脉倾向NNW,倾角70°左右。矿脉厚度从几厘米到

[收稿日期] 2013-09-26;[修订日期] 2014-01-15;[责任编辑] 郝情情。
[基金项目] 老矿山典型矿床成矿规律总结研究(项目编号:121200113086300)和国家自然科学基金项目:广东河台金矿富矿包中金的超常富集机制研究(No.41172082)资助。
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几十米不等。含矿糜棱岩平面上呈左阶斜列产出(图1中云西矿床、高村矿床、后迳矿床对应的糜棱岩),呈右旋走滑运动,剖面上产状比较稳定。与矿化相关的蚀变作用主要有烟灰色的硅化与细粒它形的黄铁矿化。伴生金属矿物主要包括黄铜矿、黄铁矿、磁黄铁矿、菱铁矿、毒砂;非金属矿物主要有石英、绢云母(刘伟等,2006)。矿区西部出露黑云母斜长花岗岩,其U-Pb同位素年龄为209~242Ma(陈骏等,1993),东部出露巨斑状黑云母二长花岗岩,其单颗粒锆石U-Pb年龄为153.6±2.61Ma(翟伟等,2005)(图1)。河台金矿可分为糜棱岩化成矿期(王鹤年等,1989;陈骏等,1993;何文武等,1993;姚德贤,1995;翟伟等,2006;朱江建等,2011a)与热液成矿期(王鹤年等,1989;何文武等,1993;陈骏等,1993;Zhang et al.,2001;翟伟等,2006)。其中糜棱岩化成矿期形成小于1g/t的金活化(陈骏等,1993;姚德贤,1995)。糜棱岩中多硅白云母Ar-Ar年龄为187~192 Ma(蔡建新,2012)。热液成矿期是河台金矿主要的成矿期,据前人研究其总体可分为金-黄铁矿-石英阶段、金-石英-多金属硫化物阶段以及金-硫化物-碳酸盐脉阶段(王鹤年等,1989;何文武等,1993;陈骏等,1993;Zhang et al.,2001;翟伟等,2006)。其中金-黄铁矿-石英阶段、金-石英-多金属硫化物阶段是河台金矿主要的热液成矿阶段,其硫化物Pb-Pb年龄、富硫化物石英脉中锆石U-Pb年龄、富硫化物石英脉中磁黄铁矿Re-Os年龄为150~175±4.3Ma(张志兰等,1989;水汀等,1997;翟伟等,2006;王成辉等,2012)。

2　河台金矿矿体的近等距性

2.1　平面上的近等距性

9、19、11、12、13号糜棱岩化带是河台金矿主要所含矿糜棱岩化带(其中云西矿床主要由9、19号糜棱岩化带组成、高村矿床主要由11号糜棱岩化带组成、后迳矿床主要由12、13号糜棱岩化带组成),它们在平面上具有左阶近等距的分布规律(图2a);河台金矿的富矿包平面上也有左阶近等距的分布规律(图2b)。

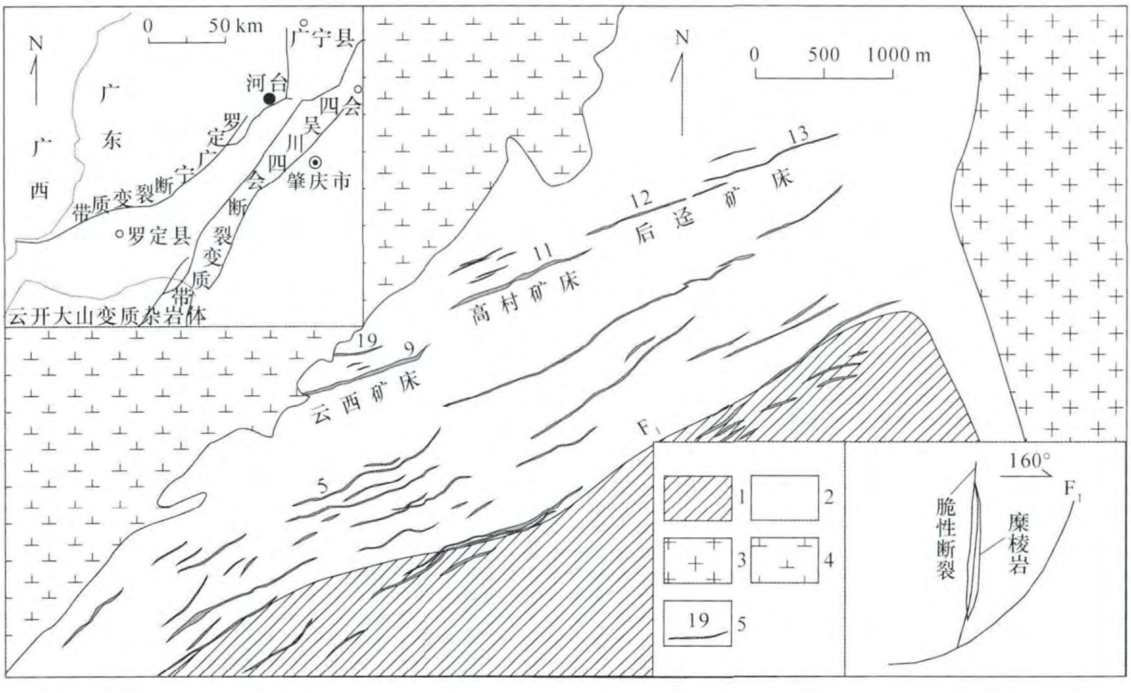

图1　河台金矿区地质简图(据朱江建等,2011b;朱江建等,2012,修改)

Fig. 1　Simplified geological map of the Hetai gold deposit, Guangdong Province (modified from Zhu *et al.*, 2011b; Zhu *et al.*, 2012)

1-奥陶系薄层浅变质砂岩、粉砂岩及薄层板岩;2-震旦系局部混合岩化的石英云母片岩、石英岩;3-巨斑状黑云母二长花岗岩;4-黑云母斜长花岗岩;5-糜棱岩化带及其编号

1-thin-bedded epimetamorphic sandstone, siltstone and thin-bedded slate of Ordovician system; 2-partial migmatited quartz-mica schist and quartzite of Sinian system; 3-macroporphyritic biotite monzonitic granite; 4-biotite plagiogranite; 5-mylonitized zones and their numbers

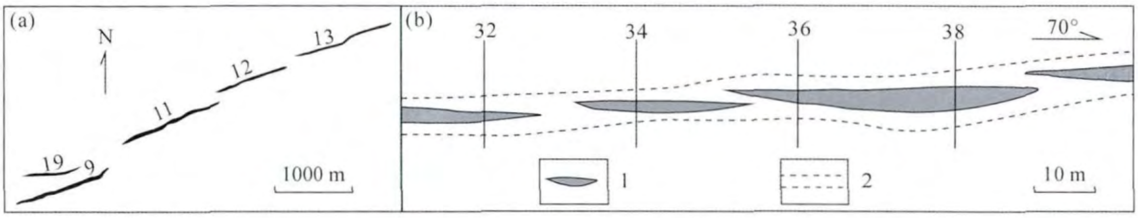

图 2　含矿糜棱岩及富矿包在平面上的近等间距排列

Fig. 2　Near equidistance pattern of mineralized mylonites and bonanzas on plane

a－含矿糜棱岩化带的左阶近等间距排列,图中数字代表矿区糜棱岩化带的编号(据朱江建等,2011a 修改);

b－河台金矿富矿包左阶近等间距排列

a－left step and near equidistance pattern of ore bearing mylonitized zones, numerals represent the numbers of mylonitized zones in the deposit (modified after *et al.*, 2011a); b－left step and near equidistance pattern of bonanzas in the Hetai gold deposit; 1—bonanza; 2—borasca

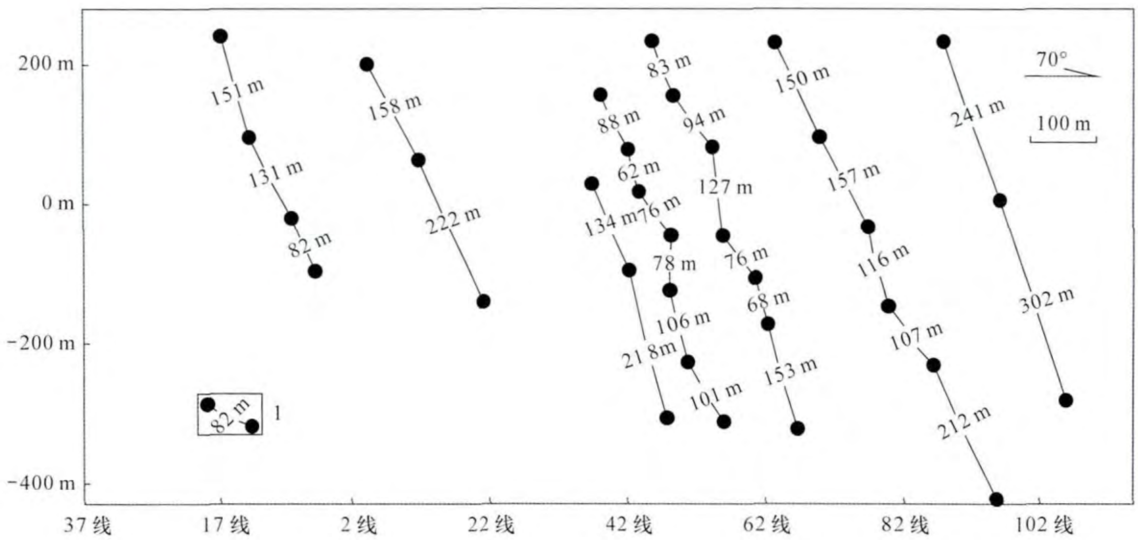

图 3　高村矿床品位富集中心在侧伏方向上的近等距性

Fig. 3　Near equidistance of grade enrichment centers in dipping direction in the Gaocun deposit

1－品位富集中心及其距离

1－grade enrichment center and their distances

2.2　剖面上的近等距性

据统计,河台金矿云西矿床相邻品位富集中心在侧伏方向上的距离为 85～179m(图 3);河台金矿高村矿床品位富集中心在侧伏方向上的距离为 62～302m(图 4)。

3　糜棱岩化之后的热液成矿期数值模拟

3.1　实验条件

本文用 FLAC 软件对河台金矿糜棱岩化之后的热液成矿期进行了平面数值模拟研究。FLAC(Fast Lagrangian Analysis for Continuum)即连续介质快速拉格朗日分析,它是基于拉格朗日元法的显式有限差分程序(龚纪文等,2002)。模拟所遵循的方法原理见(朱江建等,2011a)。

本区含矿韧性剪切带穿切云楼岗岩体(即图 1 西部的黑云母斜长花岗岩,鲍庆忠,2002),而 5 号糜棱岩化带(图 1)的围岩为混合岩,说明云楼岗岩体与混合岩的形成时间早于本区的糜棱岩。云楼岗岩体的同位素年龄(209～242Ma,陈骏等,1993)与混合岩的同位素年龄(239. 6Ma,翟伟等,2006)早于糜棱岩的同位素年龄(187 ～192 Ma,蔡建新,2012),支持了如上地质认识的合理性。结合热液成矿期的年龄为 150～175±4. 3Ma(符力奋,1989; 张志兰等,1989; 水汀等,1997; 翟伟等,2006; 王成辉等,2012),建立热液成矿期(150～175±4. 3Ma)本区的地质模型(图 5),节理统计结果表明河台金矿糜棱岩化之后的水平主压应力为 90°～114. 5°(周浩等,2014),这与河台金矿糜棱岩化期 108°(朱江

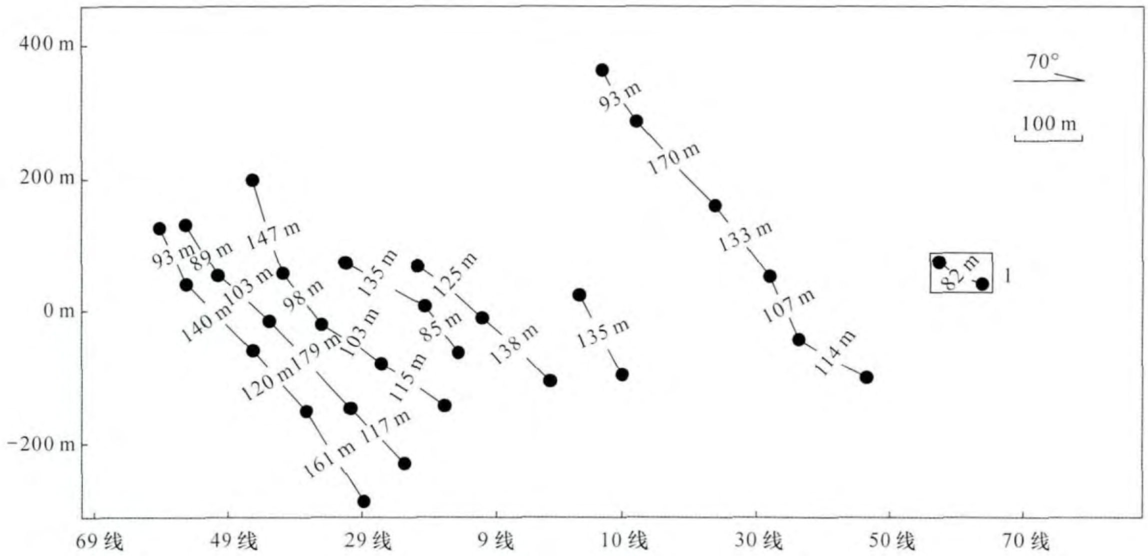

图4　河台金矿云西矿床品位富集中心在侧伏方向上的近等间距性

Fig. 4　Near equidistance of grade enrichment centers in dipping direction in the Yunxi deposit

1 – 品位富集中心及其距离

1 – grade enrichment center and their distances

表1　河台金矿不同岩石相关参数表

Table 1　Parameters of different rocks in the Hetai gold deposit

岩性	密度/$kg\times m^{-3}$	体积模量 $\times10^{10}$/P	剪切模量 $\times10^{10}$/P	内聚力 $\times10^{5}$/P	抗拉强度 $\times10^{5}$/Pa	内摩擦角	渗透率 $10^{-14}m^2$	孔隙度	扩容角
云母石英片岩	2755	4.93	6.38	0.96	5.42	29.35	1.00	0.32	3
混合岩	2700	5.94	3.03	5.56	5.15	30.20	0.02	0.25	2
花岗岩	2660	4.82	2.77	6.00	10.00	29.00	0.03	0.25	2
糜棱岩	2745	3.06	5.28	0.83	2.12	30.00	8.50	0.32	5

建等，2011a）的主压应力方向一致。所以本次仍以108°的水平主压应力作为糜棱岩化之后热液成矿期数值模拟研究的边界条件（图5）。

该地质模型 X 方向（与108°平行的方向）长1605.3m，Y 方向（与108°垂直的方向）长1405.3m。由初始地质模型建立了初始地质网格。在确保网格不破裂的情况下（以确保模拟的进行）确立 X 方向的网格数为268，Y 方向的网格数为234。边界条件为上下边界 Y 方向固定，X 方向施加 $2.425\times10^{-11}s^{-1}$（取前人研究成果 $1.13\sim3.72\times10^{-11}s^{-1}$（段嘉瑞等，1992）的平均值）的双向挤压（图5）。流体密度取 $10^3kg/m^3$，初始饱和度取1，体积模量取 2×10^9Pa。

不同岩石的力学参数的选取主要根据河台金矿内部资料①，部分参考国内外相关参数（Liu and Peng，2003; McLellan and Oliver，2008）（表1）。

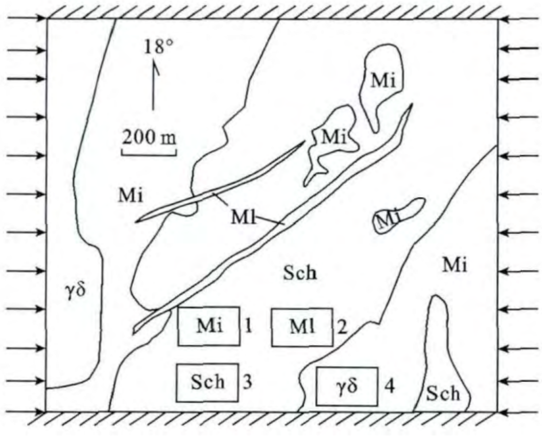

图5　热液成矿期初始地质模型与边界条件

Fig. 5　Initial geological model and boundary conditions in hydrothermal metallogenic epoch

1 – 混合岩; 2 – 糜棱岩; 3 – 云母石英片岩; 4 – 黑云母斜长花岗岩

1 – migmatite; 2 – mylonite; 3 – mica quartz schist; 4 – biotite plagiogranite

3.2　模拟结果

模拟结果显示，当区域挤压变形量达到0.686%时，研究区内分布有四条NEE向平行排列的剪切应变异常带，其值分布于0~0.03。Ⅰ号异常带平直，异常值以0.005~0.015为主；Ⅱ号异常

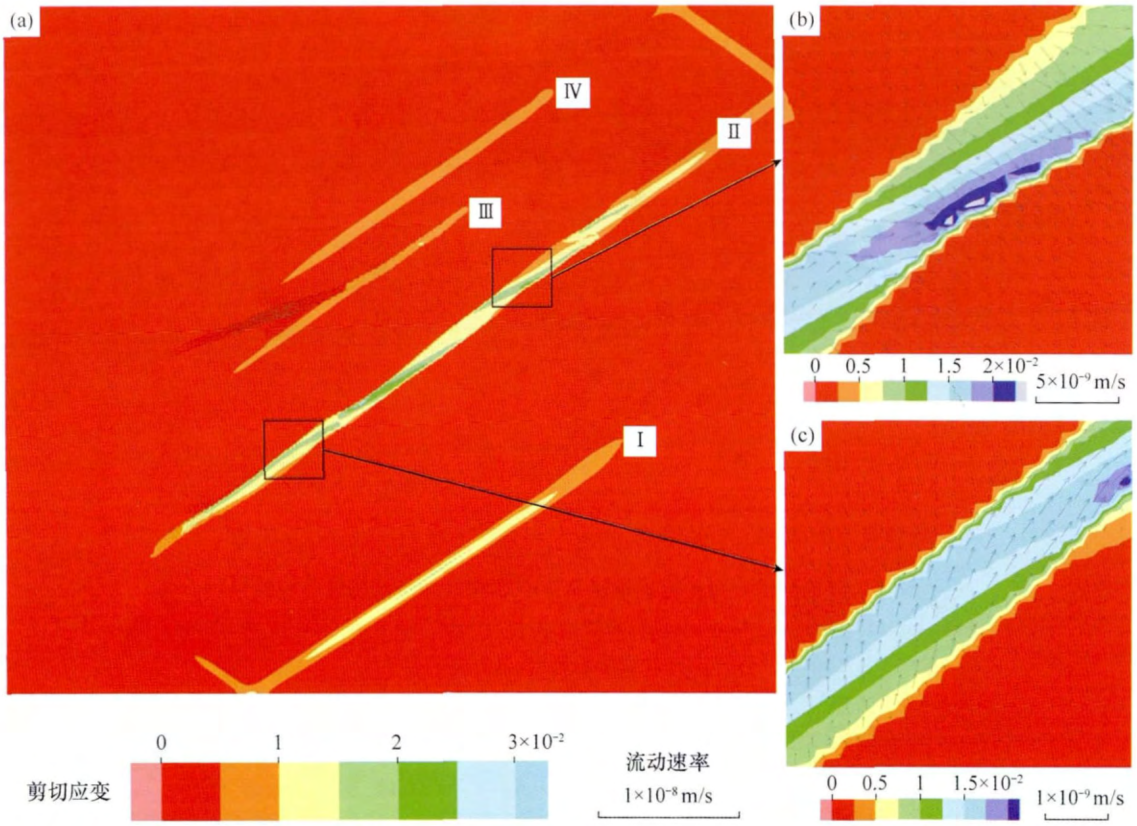

图 6 剪切应变异常带(a) 及其流体的运移图(b、c)

Fig. 6 Anomalous belts of shear strain (a) and fluid migration(b, c)

带变化较大，异常值以 0.005 ~0.025 为主，其中 0.015 ~0.025 的异常带呈左阶近等距分布; Ⅲ号异常带平直，异常值以 0.005 ~0.01 为主; Ⅳ号异常带平直，异常值也以 0.005 ~0.01 为主(图 6) 。其中Ⅱ号异常带的位置(图 6) 与本区的 9 号糜棱岩化带的位置(图 1、图 5) 一致，0.015 ~0.025 的异常带呈左阶近等距分布的规律(图 6) 与河台金矿富矿体左阶近等距的分布规律一致(图 2b) 。

4 讨论

4.1 剪切应变异常带近等距控矿模式

数值模拟结果揭示了河台金矿富矿体近等距排列(图 2b) 很可能的成因。即在剪切滑动之前，在矿区应力场的作用下(108°方位的挤压作用) ，形成了与富矿体分布特征(左阶近等距，图 2b) 一致的剪切应变异常带(图 6a) 。剪切应变异常带是有利于成矿的扩容区(Rice，1975; Rudnicki，1984; Ord *et al.*，1997; Upton，1998; Ridley *et al.*，2000) ，决定了矿体会沿剪切应变异常带分布(图 7) 。

剪切应变异常带对矿体的控制可能形成于剪切应变异常带形成期的剪切滑动控矿及剪切应变异常带形成之后的微裂隙扩张控矿。其中，剪切滑动控矿可能成因于糜棱岩化带所在位置较大的剪切应变量(图 6a) 及较大的流量(图 6b、c) 。这种较大的剪

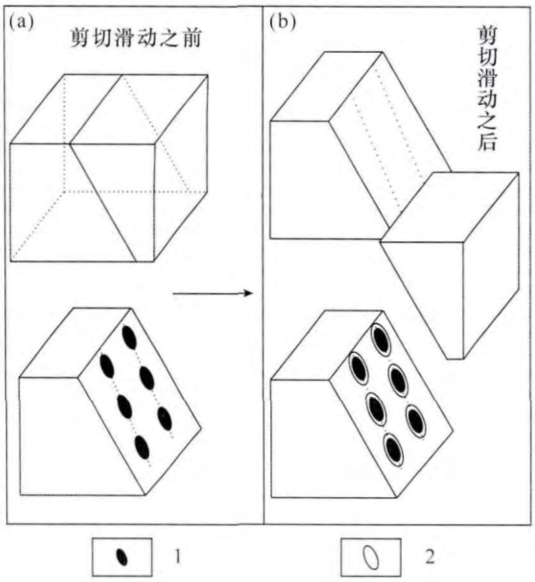

图 7 剪切应变异常带近等距控矿模式示意图

Fig. 7 Schematic diagrams of nearly equidistant ore-controlling model with anomalous belts of shear strains

1 – 剪切应变异常带; 2 – 矿体

1 – anomalous belts of shear strains; 2 – orebodies

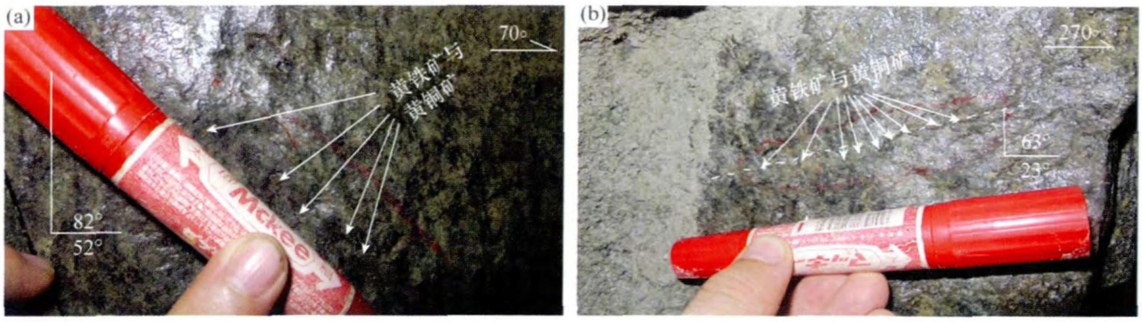

图 8　沿滑痕线理分布的含金硫化物

Fig. 8　Photos showing gold-bearing sulfides along slip lines

a－23 线－140 水平糜棱面理上的滑痕线理及沿其中分布的黄铁矿化、黄铜矿化; b－22 线－140 水平糜棱面理上的滑痕线理及沿其中分布的黄铁矿化、黄铜矿化;

a－pyrite and chalcopyrite occur along slip lines in mylonite foliation in the level －50 of line 39;
b－pyrite and chalcopyrite occur along slip lines in mylonite foliation in the level －50 of line 22

切应变量及较大的流量指示了剪切应变异常带,尤其是其中呈左阶近等距分布的异常带,易于发生剪切滑动。以上数值模拟结果从理论上很好地解释了河台金矿沿糜棱面理发生剪切滑动的现象(图 8) 。

沿滑痕线理分布的硫化物(图 8) 指示了滑动与成矿密切的成因联系。其很可能的成因是剪切滑动所产生的低压,很可能伴随着含金热液的泵吸作用与减压沸腾成矿作用。剪切滑动的后期也可能伴随成矿作用,这是因为,流体向最大剪切应变增量异常带聚集(图 6b、c) ,增加了流体压力进而产生大量的微裂隙(刘亮明等,2008) ,在随后的应力作用过程中,大量微裂隙由于应力集中而不断扩展,这为后期的热液成矿作用孕育了良好的容矿空间。综上所述,剪切滑动之前剪切应变异常带的近等距性(图 7a) 决定了剪切滑动后矿体的近等距性(图 7b) 。以上控矿模式称为剪应变异常带近等距控矿模式。这种模式较好地解释了河台金矿富矿体近等距分布的规律。

4.2　该模式可能的应用前景

基于河台金矿剪应变异常带近等距的控制富矿体,朱江建等(2012b、2013) 统计了河台金矿品位×厚度富集中心的侧伏角及在侧伏方向的距离,并将统计分析的结果进行矿体统计分析预测(朱江建等,2012b) ,且在预测区有较好的找矿效果。前人研究表明,大量矿床表现为近等距性,以金矿的近等距性为例,就有招远－掖县金矿化集中区(魏民等,1995) 、戈枕金矿带上的各金矿田(郭晓东等,1997) 、夹皮沟金矿带(魏民等,1995) 、小秦岭地区金矿脉亚矿带(王可勇等,1995) 、烧锅营子金矿区(郑超等,1995) 、胶东地区金矿床(孙宗锋等,1999; 郭涛等,2007) 、陕西双王金矿(汪劲草,2001) 、湘东北的大洞金矿体(符巩固等,2002) 、牟乳金矿(贺振等,2006) 、桃花金矿床各矿段(徐锦明,1997) 、东坪金矿(李少众,1999) 、胶东望儿山金矿(方金云,1999) 、马滑沟矿床(韦昌山等,2000) 、铧尖金矿(闫永福,2005) 、内蒙古安家营子金矿田(孟祥秋等,2008) 、山东招远界河金矿(陈静等,2009) 、峪耳崖金矿床(肖振等,2010) 等。这些金矿的近等距性很可能为剪应变异常带的近等距性所控制。由相似类比原则,将该模式控制的近等距性的矿体进行矿体统计分析预测(朱江建等,2012b) ,有望实现一定的找矿效果。

5　结论

(1) 9、19、11、12、13 号糜棱岩化带是河台金矿主要所含矿糜棱岩化带,它们在平面上具有左阶近等间距排列的规律; 河台金矿的富矿在平面上也有左阶近等间距排列的规律。

(2) 统计结果表明,云西矿床相邻品位富集中心在侧伏方向上的距离为 85～179m; 高村矿床品位富集中心在侧伏方向上的距离为 62～302m,具有一定的近等距性。

(3) 剪切滑动之前剪切应变异常带的近等距性决定了剪切滑动后矿体的近等距性。以上控矿模式称为剪应变异常带近等距控矿模式。这种模式较好地解释了河台金矿富矿体近等距分布的规律。将该模式控制的近等距性的矿体进行矿体统计分析预测,有望实现一定的找矿效果。

致谢 北京矿产地质研究院王玉往研究员和李德东博士对本文提出了建设性的修改意见，作者在此表示忠心的感谢!

[注释]

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A Nearly Equidistant Ore-Controlling Model for Shear-Strain Anomaly Belts: An Example of the Hetai Gold Deposit in Western Guangdong Province

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Abstract: In order to provide a scientific basis for prospecting at depth, this paper studies the distribution character of bonanzas and carries out numerical simulations on hydrothermal metallogenic epoch after mylonitization in the Hetai gold deposit of western Guangdong Province. The results show that bonanzas are distributed in left step and nearly equidistant on plane, also nearly equidistant on a vertical section, and dipping northeast. It is 85 ~ 179m to the adjacent bonanza in dipping direction in the Yunxi deposit, and 62 ~ 302m to the another one in pitching direction in the Gaocun Deposit. The anomalous belts of shear strains by numerical simulations are the places favorable for sliding and mineralization in the Hetai gold deposit. These anomalous belts of shear strains are also left step and nearly equidistant, same as the distribution character of bonanzas. The near equidistance of the anomalous belts of shear strains before shear sliding controlled the near equidistance of ore bodies after shear sliding. This is called the nearly equidistant ore-controlling model with anomalous belts of shear strains. Such controlling was probably determined by shear sliding when the shear strains anomalous belts were forming and by micro crack expansion after the shear strains anomalous belts had formed. Applying this model to statistical analysis and prediction of ore bodies in the deposits would help improve the effect of ore-search efforts.

Key words: the Hetai gold deposit, mylonite, near equidistance, ore-controlling model, the anomalous belts of shear strains