30wt.%NaCl当量的Na-Ca-Cl溶液。白云石中的包裹体含有不等量的CO_2。其冰点为－56.6±0.2℃，这表明了它的纯度。认为石英形成于160℃，可能高达191℃，而白云石提供的均一温度较低，为119.5℃—144.7℃。如果NaCl是饱和的，矿化过程的压力估计为750bar。当平均岩石静压力梯度为260bar/km时，则可以推论，矿化发生于不整合之上堆积了2900m沉积物的深处。因此，这些资料说明，这些金属矿床是沉积盆地演化到了相对成熟阶段从一种热的、很咸的地层水中形成的。初始矿化年代值为1000—1250Ma证实了成矿发生在沉积期后，初始矿化较Athabasca砂岩本身（1350±50Ma）要年青些。这种成因机制已被Hoeve和Sibbald（1978）归为成岩——热液作用，并进一步得到以下两方面研究的支持：（1）流体的氢氧同位素性质与现代地层水相似（Pagel和Sheppard，1980），（2）从Carswell Dome地区和盆地中央的Rumple Lake地层占孔采的碎屑颗粒上的成岩石英加大边中的包裹体也含高盐度（29—33wt.%NaCl当量）流体（pagel，1975）。估算硅化时可能已有4800m厚的沉积盆地的底部的温度约为220℃。因此从某些方面来说，形成北Saskathewan铀矿床的流体的成因和总的特征相似于形成MVT矿床的热水溶液。然而，这个以碎屑沉积为主的层序的底部温度约为160℃的饱和NaCl卤水的成因机制仍然是一留待明确的问题。

四、概括和结论

（a） 所有经过研究的热液成矿流体主要是碱金属（Na、K）和碱土金属（Ca）氯化物水溶液（如表9.1）。

（b） 一般说来，总成分的变化是很显著的。其盐度变化范围从某些浅成低温热液Au—Ag—Cu—Pb—Zn矿床中小于海水盐度（如Sunnyside：0.5—1.0wt%NaCl当量）到与火成侵入体有关的矿床中许多没有沸腾的热液流体典型的5—10wt.%NaCl当量（如Cligga；panasquiera；CarrockFell）；

表9—1　未受沸腾影响的热液成矿流体中有用的主要阳离子和阴离子成分

离子浓度（wt%）	科罗拉多 Sunnyside 浅成低温热液 Au—Ag—Cu—Pb—Zn脉状矿床（Sacadevall 和Ohmoto，1977）	秘鲁 Finlandia浅成低温热液 Au—Ag—Cu—Pb—Zn 脉状矿床（Kalnilli 和Ohmoto，1977）	密苏里碳酸盐主岩的 MVTPb—Zn±重晶石±萤石矿床（Roedder，1976）
Na^+	0.03—1.28	0.6—2.6	5.71
K^+	0.01—0.27	0.06—0.53	0.27
Ca^{++}	0.03—1.82	0.06—0.56	1.80
Mg^{++}	0.007—0.094	0.004—0.2	0.24
Cl^-	0.2—1.8	1.1—4.2	12.46
溶解固体的总量	0.4—3.5	1.8—7.1	20.38

再到密西西比河谷型(MVT)和砂岩主岩Pb—Zn±重晶石±萤石矿床的15—25wt%；再到斑岩铜矿的钾蚀变核和其它水溶液沸腾很显著的矿床的40—60wt%。在最后一类矿床中，某些流体可以含有比水更多的溶解盐（wt%），因此可以称为水盐熔体。

（c）　矿床的特定类型可以表现出一定的成分范围和特征：如蛇绿岩火山成因的硫化物矿床为3wt%NaCl当量，日本黑矿型矿床的网脉矿为2—8wt%NaCl当量；浅成低温热液Au—Ag—Cu—Pb—Zn脉±交代矿床为0.5—12wt%NaCl当量；具沸腾证据的斑岩铜矿核部为40—60wt%NaCl当量；

与火成岩侵入体共生而不发生沸腾的某些矿床为5—10wt% NaCl当量(如Carrock Fell, Cligga, Panasquiera)。

密西西比河谷型矿床和主岩为砂岩的Pb—Zn±重晶石±萤石矿床为15—25wt%，其包裹体不沸腾，无子晶，二价阳离子含量高并捕获有石油。

(d) 热液金属矿床中流体包裹体的CO_2含量变化很大，在某些斑岩铜矿和各种各样Mo、W(Higgins, 1980)、Sn和U矿床中能见到高浓度CO_2。

(e) 总的说来，对各类热液矿床所推断的形成温度差异也是很大的。其变化范围从MVT矿床的80℃，到斑岩铜矿核部高达700℃。

(f) 矿床的特定类型也能表现其一定的形成温度范围：

如：蛇绿岩和黑矿型火山成因硫化物矿床的高位网脉矿为260—330°C；

浅成低温热液Au—Ag—Cu—Pb—Zn脉状矿±交代矿床为200—330°C；

斑岩铜矿核部为400—700°C；

与斑岩铜矿共生的钾长石分解蚀变为200—400℃；

与火成岩侵入体共生的许多矿床为200—400°C(如Cligga西部为200—400°C；Panasquiera西部为230—360°；Pastō Bueno W—Cu—Pb—Ag主要和晚期矿脉为175—290°C；La Crouzille U矿床为345°C)；

MVT和主岩为砂岩的Pb—Zn±重晶石±萤石矿床为80—150°C，可高达220°C。

(g) 成矿期间温度降低是热液矿床中经常观察到的特征。最后期的共生阶段常以硫酸盐、碳酸盐±萤石为特征，其形成温度为80—150°C。这种模式大概是反映了热源与流体源的衰退。

(h) 含水相的沸腾在热液矿床的形成中是一种变化多端的现象。

例如：（i）携带高浓度金属的沸腾盐水溶液或水盐熔体看来是斑岩铜矿钾蚀变核心无处不有的特征。由这样一个"蒸汽发动机"作用而产生的高压与岩浆结晶释放的不可逆流体一起可以在形成和保持由水压作用的裂隙渗透性起重要作用。

（ii）在火山成因硫化物矿床、浅成低温热液Au—Ag—Cu—Pb—Zn矿床、次火山Sn—Ag矿床、蓆状脉矿床和脉状矿床等形成期间含水相沸腾的发生看来是变化无常的，因此，推测在矿石沉淀过程中一般并不重要。例如，在Sunnyside、Idarado和Finlandia的Ⅰ阶段和Ⅱ—Ⅵ阶段浅成低温热液矿化期间没有沸腾的证据，而在Finlandia Ⅱ阶段和Casapalca则有沸腾的证据。与此相似，在Cligga、Panasgui-era和Carrock Fell的蓆状脉和脉状矿化期间没有沸腾的证据，而在Goonbarrow Pasto Bueno和玻利维亚的Sn—w矿床则有沸腾的证据。

（iii）在MVT和碳酸盐为主岩的脉状Pb—Zn±重晶石±萤石矿床没有发现沸腾的证据。

（i）某些类型热液矿床的形成深度根据流体包裹体和其它研究估计为：

例如：浅成低温热液Au—Ag—Cu—Pb—Zn矿床约为500m；斑岩铜矿床约为1800—3000m。

（j）在热液体系中矿石沉淀的某些机制或者根据流体包裹体研究得到了推断，或者得到流体包裹体研究的支持：

（Ⅰ）随传导热损失（给冷却的围岩）而沉淀。这个过程通常认为是会发生的，尤其是在脉状矿床中。矿化期间热液的衰减可以成为这一论点的证据，这表明围岩相对是冷的。然而有关矿脉的某一特定共生阶段内的垂直热梯度或由矿脉至围岩的热梯度的令人满意的证据是有限的。英国北部的Alston断块中的碳酸盐为主岩的脉状Pb—Zn—萤石—重晶

石矿床中流体温度降低与各矿物带之间良好的关系是一个例外（Sawkins，1966）。

（Ⅰ）冷却和由流体混合引起的化学变化，这种混合对溶解度的影响比稀释的影响大得多。这种作用发生的有力证据见于火山成因的硫化物矿床、次火山Sn—Ag矿床和通常以矿壳为标志的斑岩铜矿的钾蚀变/钾长石分解蚀变的边界处（Lowell和Guilbert，1970）。

（Ⅱ）水相沸腾。在秘鲁的FinlandiaⅡ共生阶段的厚130m的近水平带中的Au—Ag富矿石与具有沸腾证据的流体包裹体之间的联系已由Kamilli和Ohmoto（1977）作了精辟的阐述。同时在其它矿床中可能是重要的。然而水相沸腾如上面讨论的那样不可能具有普遍的重要性。

（Ⅳ）CO_2泡腾（effervescence）和铀碳酸盐络合物的不稳定性。这种作用的流体包裹体证据已经用于解释法国中央地块脉状铀矿床（Cuney，1978；Leroy，1978）。

（k） 氢和氧同位素地球化学表明，作为包裹体所捕获的形成热液矿石的流体来源犹如现代天然水类型一样是多种多样的。但是，必须强调，虽然稳定同位素研究可以指出主要的液流体的成分，但是那些具有或不具有地球化学重要性的少热量其它流体（5—10%）可能检测不到。

（Ⅰ）岩浆水占优势。如斑岩铜矿床钾蚀变核；某些浅成低温热液和脉状矿床的早期阶段，如Casapalca和Pasto Bueno矿床。

（Ⅱ）大气水占优势。如浅成低温热液Au—Ag—Cu—Pb—Zn矿脉±共生的交代矿床；斑岩铜矿的钾长石分解蚀变带。

（Ⅲ）海水占优势。如蛇绿岩和黑矿型火山成因的硫化物矿床。

（Ⅳ）含盐的地下水（地层水）占优势。如某些浅成低温热液Au—Ag—Cu—Pb—Zn矿床（Finlandia），可能还有与侵入

火成岩共生的，流体盐度为5—10wt.%NaCl当量，形成温度为200—400℃的许多类型的矿床；碳酸盐（包括MVT）和砂岩为主岩的Pb—Zn±重晶石±萤石矿床，它们与侵入火成岩没有关系；与不整合有关的U±Ni±Co矿床。

从上述小结可见，热液矿床形成于不同成分、温度和成因的多种多样的溶液。流体包裹体研究是导致认识这些矿床多种多样成因的主要途径。

（李荫清译　芮宗瑶校）

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