8.1 INTRODUCTION

This Chapter combines the geological, geochronological, mineralogical and geochemical data collected in this study to further discuss their nature and origin, with particular reference to gold occurring in the SMD gold and copper deposits. Early work by Sillitoe (1994a, b), Loader et al. (1999) and Manini et al. (2001) described the SMD as a zoned mineral district comprising (a) SHGD, (b) proximal skarn and carbonate replacement Cu-Au deposits, and (c) porphyry Cu-Mo Prospects, and the geological settings of these systems are explained in Chapter 4. In addition, Manini et al. (2001), Smith (2003), Smith et al. (2005) and Olberg et al. (2006) described the SMD SHGD as having affinities with the distal disseminated Carlin-type SHGD. Loader (1999), Cannell (2005, 2006, 2008) and Cannell and Smith (2008) report that the SMD copper deposits as having several similarities to copper skarn deposits that are located proximally to rhyodacite porphy (RDP) intrusions (Chapter 4). At the time of this study, very little previous work described the SMD porphyry Cu-Mo prospects due to the paucity of surface and drillhole information, and as a result, this style of mineralisation has not been examined in detail.

Taking into consideration the SMD gold and copper deposits styles in this study, comparisons are made in Sections 8.2 to 8.4 with other known districts containing SHGD and associated base metal resources, with particular reference to the current two largest SHGD producing districts, viz. Nevada, USA and Southern China to help identify important geological and geochemical controls involved with the development of genetic models and exploration criteria for the SMD. Section 8.2 compares the broad geological features of the SMD gold and copper deposits, drawing on the information from Chapters 2, 3 and 4. Section 8.3 considers their sulphide ore mineralogy and timing relationships based on the observations from Chapter 5 and Section 8.4 discusses their geochemical characteristics with regards to the results presented in Chapters 6 and 7.

The primary purpose of this Chapter is to use the information obtained during this study to develop ore deposit models to explain the genetic formation of gold in the SMD SHGD and the SMD copper deposits (Sections 8.5 to 8.6). In addition, the implications for gold and copper exploration in the SMD are presented in Section 8.7. This Chapter concludes with a summary of the principal SMD results and observations from this study in Section 8.8 and comments on possible future directions for research in the SMD (Section 8.9).
8.2 MODE OF OCCURRENCE

8.2.1 Regional geological setting

The SMD gold and copper deposits are hosted by Palaeozoic sedimentary rocks in the Sepon Basin, located along the Truong Son Fold Belt on the NE margins of the Indochina Terrane (Chapter 3). The regional geological setting of the Sepon Basin is interpreted to have evolved via transpressional deformation, involving (a) early sinistral movement along the Truong Son Fold Belt creating a N-S trending pull-apart basin, development of WNW-trending high angle basin-forming faults and sediment deposition during the Ordovician to Devonian; (b) intrusion of RDP along pre-existing faults during the Permo-Carboniferous (297 to 280 Ma), and (c) dextral movement along the Truong Son Fold Belt during the Indosinian between 243 and 247 Ma resulting in N-S directed compression and inversion of the Sepon Basin (Morris, 1996, 1997a, b, 1998, 2006; Leprivier, 1997, 2004; Marten 1998a, b, c; Coller, 1999; Norris, 1999; Manini et al., 2001; Smith, 2003; Smith et al., 2005; Ekins, 2005; Cromie, 2005).

For comparison, the Carlin-type gold deposits in Nevada also occur in Palaeozoic sedimentary units deposited along a palaeo-continental margin. However, their regional geological setting differs as the gold deposits are hosted by structures that underwent (a) initial rifting during the Neoproterozoic, followed by (b) regional compression during several orogenies in the Palaeozoic, forming low angle imbricate thrusts and folds, in turn by (c) regional extension during the Eocene, opening previously developed fractures, forming a basin and range rift setting with cross-cutting basinial high angle normal faults, tilted sedimentary blocks and intrusion of felsic stocks (Table 8.1; Teal and Jackson, 1997; Ressel and Henry, 2006; Hofstra and Cline, 2000; Cline et al., 2005). Also noteworthy are the distal-disseminated gold deposits (DDGD) in Nevada that contain ore-type similarities to the Nevada Carlin-type gold deposits, but differ in that they spatially occur close to granite intrusions, especially along the Battle Mountain Trend where they are close to porphyry Cu-Mo systems (Hofstra and Cline, 2000; Johnson and Ressel, 2004; Ressel and Henry, 2006). The Nevada DDGD are mainly emplaced along extensional magmatic arcs (Table 8.1, Hofstra and Cline, 2000).

The regional geological setting of the Southern China Carlin-type gold deposits is similar to the setting in Nevada as they occur (a) in Palaeozoic-Mesozoic sedimentary units, (b) within sag basins along the rifted margins of the Precambrian South China Terrane, and (c) along structural zones with intense deformation, especially where Triassic-Jurassic compressional structures such as thrust faults, folds and domes are cross-cut by strike-slip and normal faults during regional extension in the Cretaceous (Table 8.1; Liu et al., 1991; Li and Peters, 1998; Zhang et al., 2003; Peters et al., 2007). Both the Southern China and Nevada Carlin-type gold deposits occur in settings characterised by early compressional followed by late extensional, which is the opposite of the sequence for the gold and copper deposits in the SMD, involving early extensional followed by late compression of the Sepon Basin.
### Table 8.1. Comparison of the major geological and geochemical characteristics of sedimentary rock-hosted gold deposits (SHGD) in Laos, Carlin-type gold deposits in Southern China and Nevada, and also distal disseminated gold deposits (DDGD) in Nevada, USA (compiled from the references listed in this table).

<table>
<thead>
<tr>
<th>Region / Country</th>
<th>Deposit Types</th>
<th>Southern China</th>
<th>Nevada, USA</th>
<th>Nevada, USA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SMD, Laos</td>
<td>SHGD and Proximal Cu Skarn</td>
<td>Carlin-type (Au)</td>
<td>Distal Disseminated (Au)</td>
</tr>
<tr>
<td><strong>Examples</strong></td>
<td></td>
<td>Jinfeng, Yata, Banqi, Zimudang, Gaolong, Jinya, Kuzhubao, Bashishan</td>
<td>Carlin, Jerritt Canyon, Getchell, Twin Creeks, Betze Post Screamer</td>
<td>Battle Mountain, Bullion, Cove Eureka, Robinson</td>
</tr>
<tr>
<td><strong>Largest Deposit Size</strong></td>
<td>&lt;1 Moz Au (Nalou), &gt;1 M tonnes of contained Cu metal (Khanong)</td>
<td>&gt;4.5 Moz Au (Jinfeng)</td>
<td>&gt;39 Moz Au (Betze Post Screamer)</td>
<td>&gt;4 Moz Au (Lone Tree)</td>
</tr>
<tr>
<td><strong>Grade (Au)</strong></td>
<td>1.9 to 4.3 g/t Au</td>
<td>&lt;1 to &gt;18 g/t Au</td>
<td>0.6 to 29 g/t Au</td>
<td>Not published</td>
</tr>
<tr>
<td><strong>Tectonic Setting</strong></td>
<td>Early extension then compression and inversion of Sepon Basin along Indochina Terrane margins</td>
<td>Extensive rift zone along southwestern margins of South China Terrane</td>
<td>Basin and range formed during back arc extension within a magmatic arc</td>
<td>Basin and range formed during back arc extension in a diffuse magmatic arc</td>
</tr>
<tr>
<td><strong>Host Rock Ages</strong></td>
<td>Broadly Ordovician to Early Permian</td>
<td>Broadly Cambrian to Triassic, Mainly Devonian, Permo-Triassic</td>
<td>Broadly Cambrian to Devonian, Predominantly Silurian to Devonian</td>
<td>Broadly Cambrian to Devonian, Predominantly Silurian to Devonian</td>
</tr>
<tr>
<td><strong>Host Rock Types</strong></td>
<td>Calcareous shale, carbonaceous shale, dolomitic limestone, RDP</td>
<td>Silty carbonate, calcareous shale, siliciclastics, mudstone, gabbro</td>
<td>Silty carbonate, calcareous shale, siliciclastics, dolomitic limestone</td>
<td>Silty carbonate, calcareous shale, siliciclastics, calc-alkaline intrusions</td>
</tr>
<tr>
<td><strong>Igneous Association</strong></td>
<td>Spatial association with rhydacite porphyry intrusions (Early Permian)</td>
<td>Broad spatial association with minor lamprophyre dikes and gabbro sills (Triassic to Tertiary)</td>
<td>Broad spatial association with subduction related calc-alkaline (Jurassic to Eocene)</td>
<td>Subduction related calc-alkaline intrusions (Jurassic to Eocene)</td>
</tr>
<tr>
<td><strong>Controls - Ore</strong></td>
<td>Steep WNW and ENE-striking faults, folds, bedding, rheological contacts</td>
<td>Steep extensional faults, shallow thrust faults, folds, bedding, unconformities, karsted topography</td>
<td>Steep extensional faults, shallow thrust faults, breccia zones, folds, bedding</td>
<td>Steep extensional faults, shallow thrust faults, breccia zones, folds, bedding</td>
</tr>
</tbody>
</table>

Comparisons of ore mineralogy and the mineralisation ages are presented in Table 8.2. Abbreviations used: Moz = million ounces (metric); RDP = Rhyodacite porphyry.
8.2.2 Age of host stratigraphy

Lithologies hosting currently known SHGD and DDGD with Carlin-type features such as micro-disseminated type gold are reported to vary in age worldwide ranging from Precambrian though to Cretaceous, but most are currently known to occur in Palaeozoic-Mesozoic sedimentary basins (Sillitoe and Bonham, 1990; Berger and Bagby, 1991; Liu et al., 1991; Garwin et al., 1995; Presnell and Parry, 1996; Teal and Jackson, 1997; Li and Peters, 1998; Asadi et al., 1999; Thompson, 2002; Zhang et al., 2003; Cline et al., 2005; Peters et al., 2007). Some of the oldest known rocks hosting micro-disseminated type gold occur in Precambrian siliciclastic units at the Zarshuran gold deposit in north-western Iran, which is reported by Asadi et al. (1999) to share similar characteristics with the Nevada Carlin-type gold deposits, demonstrating that this style of gold mineralisation can also occur in pre-Palaeozoic rocks. However, it is important to note that the age of gold mineralisation is often younger than the host rocks (Table 8.2).

Sedimentary rocks hosting both DDGD and Carlin-type gold deposits in Nevada range in age from Cambrian to Devonian, although Silurian to Devonian transitional zone facies comprising carbonate and siliciclastic rocks are the principal hosts to gold mineralisation (Table 8.1; Teal and Jackson, 1997; Thompson, 2002; Peters et al., 2003; Johnston and Ressel, 2004; Cline et al., 2005). Sedimentary rocks hosting the Southern China Carlin-type gold deposits range in age from Cambrian to Triassic and are also similar in age to those hosting the Nevada Carlin-type gold deposits. Furthermore, three groups of Palaeozoic sedimentary rocks are known to host most of the Southern China Carlin-type gold deposits, comprising: (1) Lower Devonian and Upper Permian clastic rocks, (2) Permo-Triassic carbonate-bearing clastic rocks, and (3) Triassic carbonate-bearing clastic rocks (Liu et al., 1991; Li and Peters, 1998; Cromie and Khin Zaw, 2003; Zhang et al., 2003; Peters et al., 2007). Peters et al. (2007) report that Triassic carbonate-bearing clastic rocks predominantly host the largest known Carlin-type gold deposits in Southern China, namely Jinfeng (Lannigou), Yata, Zimudang and Jinya (Table 8.1). Elsewhere, deposits containing micro-disseminated type gold hosted by younger lithologies include (1) Jurassic-Cretaceous age limestone and calcareous shale intruded by Miocene porphyry stocks at Bau, Sarawak (Sillitoe and Bonham, 1990), and (2) Middle Miocene carbonate, siliciclastic and volcanoclastic rocks intruded by andesite sills and dykes at Mesel, Indonesia (Turner et al., 1994; Garwin et al., 1995).

In comparison, the ages of the SMD calcareous and siliciclastic rocks hosting gold mineralisation range from Ordovician-Early Silurian to Middle Devonian and are also similar in age to those rocks hosting the Nevada Carlin-type gold deposits (Table 8.1; Smith et al., 2005; Ekins, 2005; Olberg et al., 2006; Cromie et al., 2004a, b; Cromie et al., 2006a, b; Cromie et al., 2007). The known SMD gold resources are described by Smith et al. (2005) to be mostly hosted by the Devonian Discovery Formation calcareous shale, with lesser amounts reported in
turn for the underlying Devonian Nalou Formation bioclastic dolomite, the Silurian-Devonian Kengkeuk Formation calcareous shale and the Ordovician-Silurian Nampa Formation claystone and siltstone sequence (Chapter 3, Section 4.2).

8.2.3 Host rock types

Transitional zone sedimentary facies formed between the shallow-water platform and deep marine environments comprising argillaceous limestone, dolomitic shale, calcareous shale, pyritic mudstone and siltstone are the principal host rocks for micro-disseminated gold in both the Nevada and Southern China Carlin-type gold deposits. In comparison, the SMD SHGD also formed in a similar transitional facies sequence (Table 8.1; Teal and Jackson, 1997; Hall et al., 1997; Smith, 2003; Smith et al., 2005; Peters et al., 2007). Other variations of Carlin-type host rock associations include the Fu Ning District in the Dian-Qian-Gui region of Southern China that contains micro-disseminated gold along fault breccia zones between Triassic gabbro sills and Devonian mudstones at the Bashishan and Jinba deposits (Table 8.1; Cromie and Khin Zaw, 2003; Peters et al., 2007).

The currently known gold and base metal resources in the SMD are hosted by Palaeozoic sedimentary rocks ranging in age from Ordovician through to Early Devonian with the majority of currently known gold resources hosted by the Devonian Discovery Formation calcareous shale (Table 8.1 and Chapter 4, Sections 4.2 to 4.3). Dolomite rarely hosts large concentrations of gold in the SMD SHGD (Smith et al., 2005). The presence of a low permeability cap rock overlying gold mineralisation has only been observed at the Discovery West deposit in the SMD and comprises a transitional sequence of interbedded non-calcareous shale, siltstone and chert, interpreted to form towards the upper sections of the Devonian Discovery Formation calcareous shale and Late Devonian Nan Kian Formation siliciclastic sequence (Smith et al., 2005). The SMD copper deposits are also hosted by similar carbonate and siliciclastic rocks to those occurring in the SMD SHGD (Chapter 4, Section 4.3).

8.2.4 The association of igneous rocks

Several Carlin-type and DDGD in Nevada, Utah, Malaysia, Indonesia and Peru have igneous rocks ranging from felsic to mafic compositions in their local geological setting (Alvarez and Noble, 1988; Sillitoe and Bonham, 1990; Berger and Bagby, 1991; Garwin et al., 1995; Hofstra et al., 1999; Hofstra and Cline, 2000; Johnson and Ressel, 2004; Cunningham et al., 2004; Ressel and Henry, 2006; Johnson et al., 2008). In some districts, micro-disseminated gold occurring in the DDGD is spatially associated with igneous intrusions in zoned mineral districts comprising proximal Cu±Zn-Pb skarns and Cu-Mo porphyry centres, namely: (1) the Barneys Canyon and Melco gold deposits in the Bingham Canyon porphyry Cu-Mo district, Utah (Sillitoe and Bonham, 1990; Presnell and Parry, 1996; Gunter and Austin, 1997; Kerr, 1997; Cunningham et al., 2004), and (2) the Battle Mountain, Bullion and McCoy gold deposits
in Nevada (Sillitoe and Bonham, 1990; Johnston and Ressel, 2004; Ressel and Henry, 2006; Johnston et al., 2008). Although the formation of Cu-Mo and Cu±Pb-Zn mineralisation is coeval with particular causative igneous intrusion phases in some of these districts, there is no convincing evidence to-date that directly indicates the contemporaneous association of igneous intrusions with gold mineralisation within the currently studied Carlin-type and DDGD deposits (Hofstra and Cline, 2000; Johnston and Ressel, 2004; Cline et al., 2005; Ressel and Henry, 2006; Johnston et al., 2008). However, Johnston and Ressel (2004), Ressel and Henry (2006) and Johnston et al. (2008) propose that the Carlin-type and DDGD in Nevada are spatially associated with igneous intrusions and that larger plutons at depth possibly provided a protracted heat source over a period of >4 Ma during the Eocene to enhance hydrothermal circulation in the gold districts during mineralisation.

Igneous intrusions in some of the Nevada Carlin-type deposit districts, contain examples of epigenetic micro-disseminated gold mineralisation that occurs (a) along brittle-ductile fracture zones between igneous intrusions and sedimentary rocks, (b) in association with packages of sedimentary and volcanic rocks, and (c) within andesite and basaltic dikes and sills cutting older stratigraphy (Berger and Bagby, 1991; Hall et al., 1997; Hofstra et al., 1999; Hofstra and Cline, 2000; Cline et al., 2005). The Getchell, Gold Acres and Goldstrike Carlin-type gold deposits in Nevada are hosted by Palaeozoic sedimentary rocks at the contact with (1) Mesozoic granodioritic stocks, or (2) cross-cutting Cenozoic felsic dykes (Berger and Bagby, 1991; Cline et al., 1997; Cline, 2001). The Twin Creeks Carlin-type deposit in Nevada is hosted by a folded sequence of Ordovician dolomitic to calcareous black shales with inter-layered basaltic flows and sills and tuffaceous interbeds, where gold is mainly concentrated towards the nose of a large NW-plunging fold and between steeply dipping NE-trending faults (Hall et al., 1997; Thoreson et al., 2000). The Jerritt Canyon Carlin-type gold deposits contain gold in altered Carboniferous andesite dikes and sills and Eocene basaltic dikes and sills that both cut Ordovician to Devonian sedimentary rocks (Hofstra et al., 1999).

Magmatic activity was minor during the Triassic and Cretaceous periods in the Dian-Qian-Gui region of Southern China hosting the Carlin-type gold deposits, comprising small volume epizonal mafic and felsic intrusions that were mainly confined to the faulted margins of the South China Terrane and also in the adjoining fold belts (Peters et al., 2007). The Jinba and Bashishan gold deposits in the Dian-Qian-Gui region are examples where micro-disseminated gold mineralisation only occurs along the faulted contacts between brittle Triassic gabbro sills and more ductile Devonian siliciclastic rock types (Cromie and Khin Zaw, 2003; Peters et al., 2007). There is no current evidence such as metamorphic aureoles or chilled intrusion margins to suggest that the Triassic gabbros intrusions at either Jinba and Bashishan provided a heat source for gold-bearing hydrothermal fluids and therefore they are regarded as a structurally-prepared favourable host rock (Cromie and Khin Zaw, 2003; Peters et al., 2007).
By comparison, examples of highly deformed intrusions hosting micro-disseminated gold in the SMD SHGD have only been observed along the faulted contacts between (a) brittle Early Permian rhyodacite porphyry (RDP) and ductile Devonian Discovery Formation calcareous shale, and (b) Early Permian RDP and Devonian Nalou Formation dolomite, mainly at the Nalou, Discovery West and Discovery Colluvial deposits (Chapter 4, Section 4.2; Manini et al., 2001; Smith, 2003; Cromie, 2004; Smith et al., 2005). Thin dolerite dikes were also observed to cut an RDP intrusion containing SMD Stage 3 sulphides at the Discovery Colluvial gold deposit, but were not able to be constrained by dating in this study but are interpreted to post-date Early Permian RDP emplacement (Chapter 3, Section 3.4).

8.2.5 Structural controls

The Carlin-type gold deposits formed in Nevada and in the Dian-Qian-Gui region, Southern China both have a structural history of early compression involving low angle thrust faulting followed by later extension that produced high angle normal and strike-slip faults (Table 8.1). Permeability generated during deformation allowed hydrothermal fluids to be focussed into structurally prepared sites, resulting in the formation of micro-disseminated gold in both the Nevada and Southern China Carlin-type gold deposits. Common structural sites favourable to gold mineralisation in both districts include (1) faults around dome margins, (2) fold axis hinge zones, (3) faulted unconformity contacts, (4) the junctions of early thrust faults cross-cut by normal and/or strike slip faults, and (5) fault breccia zones (Table 8.1; Liu et al., 1991; Teal and Jackson, 1997; Li and Peters, 1998; Hofstra and Cline 2000; Cline et al., 2005 and Peters et al., 2007).

By comparison, the integral structural components involved in the development of the SMD gold and copper deposits are also predominantly steep faults, folds and rheological contacts (Smith, 2003; Smith et al., 2005; Olberg et al., 2006). The principal structural trends controlling and hosting gold mineralisation in the SMD gold deposits are (1) WNW-striking normal faults with steep dips, and (2) steep ENE-striking faults with both normal and reverse movements (Smith, 2003; Smith et al., 2005). Gold ore zone geometries observed to date in the SMD include (1) ribbon-like bodies that are strike continuous, (2) moderately to shallowly dipping sheets, not always connected to faults, and (3) fault controlled steep sheet-like bodies (Table 8.1; Smith, 2003; Smith et al., 2005). The main-gold ore SMD Stage 4A high-grade mineralisation occurring in the SMD SHGD is epigenetic and commonly occurs along steep faults cutting Ordovician to Devonian sedimentary rocks and the margins of Early Permian RDP dykes and sills (Chapter 4, Section 4.2).
8.3 GOLD ORE MINERALOGY

8.3.1 Prelude

The paragenetic investigations presented in Chapter 5 provided insights into three main styles of district-wide hypogene mineralisation in the SMD, comprising (1) adjacent to distal type SHGD (Section 5.2), (2) proximal Cu skarns with associated supergene copper (Section 5.3), and (3) RDP intrusion centres with porphyry style Cu-Mo (Section 5.4). The individual mineral paragenesis studies presented for these three mineral deposit styles were summarised into a combined SMD mineral paragenesis that comprises at least five mineral assemblage groups, namely SMD Stages 1 to 5. Common paragenetic links observed in the combined SMD mineral paragenesis for the distal, proximal and central deposit type settings were indicated through the occurrence of gold in sulphides from the SMD Stages 3B, 3C and 4A mineral assemblages (Chapter 5, Section 5.8). This section discusses and compares the SMD mineral assemblage groups with other known deposit examples, in particular (a) Carlin-type gold deposits, and (b) distal disseminated-type gold deposits (DDGD) occurring in zoned minerals districts with skarn and porphyry Cu-Mo-Au systems (Table 8.2).

8.3.2 Alteration

Alteration styles typically observed in the Carlin-type gold deposits in Nevada and the Dian-Qian-Gui Region, Southern China comprise decarbonatisation involving the removal of the carbonate from predominantly calcareous host rock types, and variable silicification (jasperoid and/or quartz stockwork vein development). Deposits in both of these regions may also exhibit the effects of argillisation (i.e. deposit margins dominated by kaolinite and illite, in particular, intrusion contacts) and sulphidation (Arehart, 1996; Teal and Jackson, 1997; Hofstra and Cline, 2000; Heitt et al., 2003; Cline et al., 2005). Specific alteration types occurring only within some of the Dian-Qian-Gui Carlin-type gold deposits include variable amounts of carbonisation (i.e. addition of carbon), dolomitisation, baritisation and albitisation (Li and Peters, 1998; Zhang et al., 2003; Peters et al., 2007). Furthermore, most of the Dian-Qian-Gui Carlin-type gold deposits are hosted in dominantly non-carbonate rocks such as siliciclastics, which cannot display decarbonatisation (Li and Peters, 1998; Peters et al., 2007).

Similar alteration types have also been observed in the SMD SHGD, involving variable decarbonatisation of carbonate units, silicification along permeable horizons and faults, locally developed argillisation along RDP contacts and variable dolomitisation of carbonate units (Smith, 2003; Smith et al., 2005; Cromie, 2004, 2005, 2006). Pervasive silicification forming jasperoids is the predominant alteration type observed in the SMD SHGD (Smith et al., 2005). Furthermore, the primary sulphide zones hosting copper mineralisation proximal to RDP intrusions can also show sericite alteration along intrusion margins, in addition to (a) early prograde garnet and pyroxene skarn alteration cut by later retrograde chlorite-epidote alteration.
of carbonate host units, and (b) hornfels in non-calcareous sedimentary rocks (Loader, 1999; Smith, 2004a; Cromie, 2004; Cannell and Smith, 2008).

8.3.3 Paragenetic comparison of gold and associated minerals in the SMD SHGD

A common characteristic of Carlin-type gold deposit mineral assemblages is the presence of refractory gold that is typically micron-sized, disseminated and hosted by sulphides, mainly pyrite (Cline et al., 2005). The principal regions containing examples of Carlin-type gold mineralisation include (1) Nevada, USA (Radtke et al., 1980; Bagby and Berger, 1985; Kuehn and Rose, 1995; Hofstra and Cline, 2000; Emsbo et al., 2003; Cline et al., 2005) and (2) the Dian-Qian-Gui district, southern China and the Chuan-Shan-Gan district of central China (Cunningham et al., 1988; Ashley et al., 1991; Liu et al., 1991; Li and Peters, 1998; Hu et al., 2002; Cromie and Khin Zaw, 2003; Zhang et al., 2003; Peters et al., 2007).

At least three main mineral assemblage groupings are described for the Nevada Carlin-type gold deposits, comprising (a) pre-main gold ore stage, followed by (b) main gold ore stage, and (c) post-main gold ore stage (Table 8.2; Ferdock et al., 1997; Cline et al., 1997; Cline et al., 2005). These three main mineral assemblage groupings are also described for the Dian-Qian-Gui Carlin-type gold deposits (Cunningham et al., 1988; Li and Peters, 1998; Peters et al., 2007) and the SMD SHGD (Cromie et al., 2006a, b, 2007). Common ore minerals occurring in all three gold districts include major pyrite, arsenopyrite, arsenian pyrite, arsenian marcasite, marcasite, stibnite, and minor orpiment, realgar, sphalerite, galena, chalcopyrite and barite (Table 8.2). Gangue minerals common to all three gold districts are quartz, kaolinite, smectite, illite, and calcite, with minor associations with iron carbonates, and dolomite hypogene alunite (Ferdock et al., 1997; Cline et al., 1997; Cromie and Khin Zaw, 2003; Heitt et al., 2003; Cline et al., 2005; Cromie et al., 2006a, b; Peters et al. 2007).

8.3.3.1 Pre-main gold ore stage mineral assemblages in Carlin-type gold deposits

The pre-main gold ore stage minerals occurring in the Nevada Carlin-type gold deposits comprise (a) early calcite, (b) base metal assemblages consisting of quartz, sericite, pyrite and minor chalcopyrite, sphalerite, galena and barite, (c) calcite dissolution (decarbonatisation) of calcareous host rocks accompanied by sericite alteration and (d) early jasperoid development in open spaces (Ferdock et al., 1997; Cline et al., 1997; Teal and Jackson, 1997; Cline et al., 2005; Table 8.2). Cline et al. (2005) report that the pre-ore compositions of wall rocks, preferential dissolution of calcite and sulphidation of carbonate minerals can all contribute towards generating a variety of pre-gold ore carbonate minerals such as calcite, siderite, ankerite or dolomite. Additionally, in most of the Nevada Carlin-type gold deposits where variable amounts of dissolution of the carbonate rocks occurred, the host rock porosity was significantly increased, allowing these zones subsequently to be replaced by quartz to form jasperoid (Cline et al., 2005).
Table 8.2. Comparison of the mineral assemblages and stages for the Carlin-type gold deposits in Nevada (USA) and the Dian-Qian-Gui (southern China) with the SMD SHGD (Laos).

<table>
<thead>
<tr>
<th>Regions / Stages</th>
<th>Carlin-type (Au) Nevada, USA</th>
<th>Carlin-type (Au) Dian-Qian-Gui, China</th>
<th>SHGD (Au) SMD, Laos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposit Examples</td>
<td>Carlin, Twin Creeks, Miekle, Deep Star, Post-Betze, Gold Quarry</td>
<td>Jinfeng (Lannigou), Yata, Banchi, Zimmudang, Gaolong, Jinya, Kuzhubao (Gedang)</td>
<td>Nalou, Discovery West, Discovery Colluvial, Discovery Main, Discovery East, Namkok East, Namkok West</td>
</tr>
<tr>
<td>Pre-main gold ore stage minerals</td>
<td>(a) Early: calcite</td>
<td>(a) Early sedimentary pyrite (nodular)</td>
<td>(a) Early (SMD Stage 1): pyrite (framboidal), ferroan dolomite, calcite</td>
</tr>
<tr>
<td></td>
<td>(b) Main: quartz, sericite, pyrite, pyrrhotite, chalcopyrite, sphalerite, galena, arsenopyrite</td>
<td>(b) Late - quartz, sericite, pyrite (diagenetic)</td>
<td>(b) Main (SMD Stage 2): calcite, diagenetic pyrite (&lt;0.3 ppm Au in Pyrite 2A - C)</td>
</tr>
<tr>
<td></td>
<td>(c) Late: jasperoid (massive quartz replacement)</td>
<td></td>
<td>(c) Late (SMD Stage 3A): pyrite, sphalerite, galena, dolomite (No Au detected)</td>
</tr>
<tr>
<td>Main gold ore stage minerals</td>
<td>(a) Main - jasperoid (massive quartz), quartz (drusy), pyrite (Au and As) marcasite (Au and As), orpiment, realgar, galkhaite, fluorite</td>
<td>(a) Early - quartz, sericite, arsenopyrite</td>
<td>(a) Early (SMD Stage 3B): Quartz (vein), sericite, pyrite (&lt;3 ppm Au in Py-3B), sphalerite, galena; (b) (SMD Stage 3C): Quartz, chalcopyrite (&lt;0.9 ppm Au), sulphosalts (Cu-Sb-As)</td>
</tr>
<tr>
<td></td>
<td>(b) Late - jasperoid (massive quartz), quartz (drusy), marcasite, stibnite, orpiment, realgar, calcite</td>
<td>(b) Main - quartz, pyrite, arsenopyrite, marcasite,ankerite (high grade gold reported in pyrite)</td>
<td>(c) Main (SMD Stage 4A): Quartz (jasperoid), disseminated pyrite (Py 4A1 to Py 4A4: 1 to &gt;200 ppm Au)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(c) Late - quartz, pyrite, arsenopyrite, marcasite (low-grade gold in late pyrite)</td>
<td>(d) Late (SMD Stage 4B): Quartz, tellurides (Hg-Au)</td>
</tr>
<tr>
<td>Post-main gold ore stage minerals</td>
<td>Quartz, calcite, Fe-oxides, barite</td>
<td>Quartz, realgar, cinnabar, stibnite, sphalerite, barite, fluorite, calcite</td>
<td>(SMD Stage 5): Quartz, stibnite, dolomite, calcite (No Au detected)</td>
</tr>
<tr>
<td>Gold Epoch</td>
<td>Au (SHGD): Tertiary: 42 - 36 Ma (Cline et al., 2005)</td>
<td>Au (SHGD): Cretaceous: 100 Ma (Cunningham et al., 1988)</td>
<td>Cu (SKN): Permian 287 - 280 Ma; Au (SHGD): Post 280 Ma (This study)</td>
</tr>
</tbody>
</table>
The pre-gold ore stage occurrence of base metals in assemblages reported in the Nevada Carlin-type gold deposits include: (a) barite-sphalerite-galena at the Carlin gold deposit (Kuehn and Rose, 1992) and (b) quartz-barite-sphalerite-pyrite at the Meikle gold deposit (Teal and Jackson, 1997). The Dian-Qian-Gui Carlin-type gold deposits mainly contain pre-main gold ore stage mineral assemblages with (a) early sedimentary pyrite, and (b) later veins with quartz, sericite and pyrite (Table 8.2; Cunningham et al., 1988; Li and Peters, 1998; Cromie and Khin Zaw, 2003; Peters, 2007). No gold has been reported for these deposits in the pre-main gold ore stage assemblages comprising base metal minerals.

In comparison, the SMD SHGD contain at least three pre-main gold ore stage mineral assemblages, namely SMD Stages 1, 2 and 3A (Table 8.2). The SMD Stage 1 assemblage consists of framboidal pyrite and early ferroan dolomite along bedding cleavage and calcite veins. Early pre-main gold ore stage calcite veins are common in all districts (Table 8.2). The SMD Stage 1 ferroan dolomite is overprinted by later gold-bearing mineral assemblages, in particular the SMD Stages 3B, 3C and 4A (Table 8.2). By comparison Yigit et al. (2006) report that pre-ore dolomite and sphalerite are overprinted by gold mineralisation in the Gold Bar Carlin-type gold deposits, Nevada. No pre-main gold ore stage dolomite is reported for the Dian-Qian-Gui Carlin-type gold deposits.

The SMD Stage 2 pre-main gold ore assemblage comprises at least three types of diagenetic pyrite that contain very low levels of gold (<0.3 ppm Au). Later stage calcite fills fractures in some SMD Stage 2 pyrites (Table 8.2). The occurrence of pre-main gold ore stage diagenetic pyrite is also noted in the Dian-Qian-Gui Carlin-type gold deposits (Peters et al., 2007; Zhang et al., 2005; Cromie and Khin Zaw, 2003). The early development of jasperoid described by Cline et al. (2005) for the Nevada Carlin-type gold deposits is not reported in the SMD SHGD (Table 8.2).

The SMD Stage 3A base metal assemblage contains no known gold and consists of pyrite-sphalerite-galena-dolomite occurring along veins and fractures cutting carbonate rocks, predominantly dolomitised Nalou Formation bioclastic limestone. This SMD Stage 3A mineral assemblage is also similar to that observed in the pre-main gold ore stage for the Nevada Carlin-type gold deposits by Kuehn and Rose (1992) and Teal and Jackson (1997) but lacks the presence of barite. Moreover, Emsbo et al. (2003) report the presence of pre-main gold ore stage Late Devonian stratiform base metal mineralisation comprising sphalerite, boulangerite, galena, barite and tetrahedrite in the Meikle and neighbouring Carlin-type gold deposits, Nevada.

The SMD Stage 1, 2 and 3A mineral assemblages appear to be broadly similar to those reported for the pre-main gold ore stages in the Nevada and Dian-Qian-Gui Carlin-type deposits, but also contain at least 4 types of pre-main gold ore stage pyrite, namely Pyrite 1 and Pyrites 2A to 2C containing <0.3 ppm Au (Table 8.2 and Chapter 5, Section 5.2).
8.3.3.2 Main gold ore mineral stages in Carlin-type gold deposits

The main gold ore mineral stages in the Nevada Carlin-type gold deposits generally have three sub-stages (Table 8.2). The first sub-stage involves early dissolution of host rock carbonate (decarbonatisation) accompanied by sericite alteration, and development of marcasite, pyrite, arsenide minerals and minor base metals. In the second sub-stage the main stage high grade gold-bearing sulphides typically consist of pyrite and marcasite with associated high concentrations of arsenic, commonly accompanied by replacement type quartz (jasperoid) and the presence of orpiment, realgar, and minor fluorite and galkhaite. The third sub-stage is characterised by late main gold ore stage veins with quartz, stibnite, orpiment, realgar and calcite (Ferdock et al., 1997; Cline et al. 1997; Hofstra and Cline, 2000; Cline et al. 2005; Yigit et al., 2007). The gold in the main gold ore stage for the Nevada Carlin-type gold deposits is typically sub-micron sized, typically hosted in arsenian pyrite containing 2 to 8 wt % As; it also occurs in discrete pyrite grains or along the arsenic enriched rims on earlier formed pyrite cores (Cline et al., 2005).

Three sub-stages hosted by fractures, veins and breccias are also interpreted for the main gold ore stage mineral assemblages in the Dian-Qian-Gui Carlin-type gold deposits (Table 8.2). The early main gold ore stage contains veins of quartz-sericite-pyrite with no high gold grades reported (Li and Peters, 1998; Cromie and Khin Zaw, 2003). The main gold ore stage comprises gold-bearing pyrite, marcasite and arsenopyrite accompanied by ankerite and quartz in veins and in replacement zones. Gold-bearing pyrite associated with the main gold ore stage is also reported to contain arsenic-enriched rims with high grades of gold (Zhang et al. 2005; Peters et al., 2007). The late main gold ore stage veins comprise quartz, pyrite, arsenopyrite, marcasite and stibnite with low grade gold, but ankerite is absent (Table 8.2; Li and Peters, 1998; Cromie and Khin Zaw, 2003; Jones, 2003; Peters et al. 2007).

By comparison, at least four mineral assemblages occur in the SMD main gold ore stage grouping, namely SMD Stages 3B, 3C, 4A and 4B (Table 8.2 and Chapter 5, Section 5.2). The SMD Stages 3B and 3C are the early main gold stage mineral assemblages characterised by low-grade gold-bearing base metal assemblages with <3ppm Au, hosted in fractures and in veins cutting both RDP and carbonate rocks, comprising (a) SMD Stage 3B quartz-massive pyrite-sphalerite-galena-dolomite, and (b) SMD Stage 3C quartz-sulphosalts of Cu-Sb-As. The SMD Stages 3B and 3C mineral assemblages are not typically observed in the Nevada and China Carlin-type gold deposits in the main gold ore stage grouping (Table 8.2). However, the SMD Stages 3B and 3C mineral assemblages are more similar to those in the DDGD types cutting intrusions to skarn and/or porphyry Cu-Mo-Au deposits, as described by Sillitoe and Bonham (1990), Cline et al. (2005), Emsbo et al. (2006) and Johnston et al. (2008).
The highest gold grades in the SMD SHGD main gold ore stage mineral assemblage are hosted by SMD Stage 4A quartz-pyrite (Table 8.2; Chapter 5, Section 5.2). Four main pyrite types containing arsenic-enriched overgrowths with from 1 to >200 ppm Au occur in Pyrites 4A1 to 4A4 (Chapter 6; Section 6.2.4.4). The SMD Stage 4A pyrites are also very similar to the zoned gold-bearing pyrite types containing very high grades of gold along the pyrite grain margins reported in both the Nevada Carlin-type gold deposits (Hofstra and Cline, 2000; Cline et al., 2005) and Dian-Qian-Gui Carlin-type gold deposits (Zhang et al., 2005; Peters et al., 2007). The ankerite observed in the Dian-Qian-Gui Carlin-type gold deposit high-grade gold intervals was not observed in the SMD main gold ore stage mineral assemblages.

The SMD Stage 4A quartz associated with SMD Stage 4A pyrite is also interpreted to be the main ore-stage quartz generation that forms the silicified replacement zones, locally described as jasperoid by Manini et al. (2001), Smith (2003) and Smith et al. (2005). The SMD SHGD ore zones containing gold in both jasperoid and non-silicified decalcified calcareous shale intervals have been observed at the Nalou and Discovery West deposits, suggesting that gold is not always associated with zones of intense silicification in the SMD (Smith, 2003; Smith et al., 2005; Leach 2005). The most intense silicification in the SMD SHGD is reported to occur in zones with intense fracturing and dissolution brecciation, in particular along the contacts between calcareous shale units occurring above dolomite or locally in contact with rhyodacite (Smith, 2003; Leach 2005). Intensely silicified zones containing high-grade gold were mainly observed along steep structures at the Nalou and Discovery West deposits, whilst at the Discovery Colluvial deposit the silicification was only observed at shallow levels, mainly in the calcareous shale units (Leach, 2005). The SMD SHGD ore zones containing intense silicification in the calcareous shale units are reported to grade upwards into zones of total decalcification with ore grade mineralisation extending into the non-silicified, decarbonatised intervals, in particular at the Discovery Main and Nalou deposits, confirming that gold is not always associated with zones of intense silicification but also can occur in weakly silicified sections within decarbonatised units (Leach, 2005). These observations about the association of gold with jasperoid and decarbonatisation zones in the SMD are also similar to those reported by Leach (2004) and Cline et al. (2005) for the Nevada Carlin-type gold deposits, where they note that (a) not all gold deposition is accompanied by the development of quartz in fractures, voids or in jasperoid replacement zones, and (b) jasperoid also varies from being barren to hosting gold and is spatially associated with gold deposits on a district scale.

The SMD late main gold ore mineral assemblage is represented by SMD Stage 4B that comprises fractures and thin veins with late stage quartz and tellurides (Hg-Au). This assemblage is not typical for the Nevada or Dian-Qian-Gui Carlin-type gold deposits but has been noted by Sillitoe and Bonham (1990) to occur in the DDGD-types located peripheral to skarn and/or porphyry Cu-Mo-Au deposits. Additionally, the Nevada and Dian-Qian-Gui
Carlin-type gold deposits commonly contain orpiment and realgar associated with the late main gold ore stage mineral assemblages. However, realgar and orpiment have not been observed in the SMD SHGD main gold ore stage. Overall, the SMD SHGD main gold ore stage has broad similarities to that observed in the Nevada and Dian-Qian-Gui Carlin-type gold deposits (Table 8.2).

**8.3.3.3 Post-main gold ore stage mineral assemblages in the Carlin-type gold deposits**

The post-main gold ore stage minerals reported for the Nevada Carlin-type gold deposits mainly comprise veins with quartz, calcite, iron-oxides and barite (Ferdock et al., 1997; Hofstra and Cline, 2000; Cline et al., 2005). The Dian-Qian-Gui Carlin-type gold deposits also contain late-stage calcite veins in the post-main gold ore stage, but may also include variable amounts of late quartz, realgar, cinnabar, sphalerite, barite, and fluorite that lack gold (Li and Peters, 1998; Cromie and Khin Zaw, 2003; Zhang et al., 2005; Peters et al., 2007). Similar minerals lacking gold have been observed in the SMD SHGD, mainly along small veins belonging to the SMD Stage 5 mineral assemblage comprising quartz, stibnite, dolomite and calcite, but realgar and orpiment have not been observed (Table 8.2; Chapter 5, Section 5.2).

**8.3.4 Gold occurrence in the SMD copper skarn zones**

The presence of later stage high grade gold cutting earlier copper-bearing retrograde primary sulphide skarn assemblages preserved under overlying supergene enriched and exotic copper ores is unique for the SMD, as described in Chapter 4 (Section 4.3). Very little information is presently available for direct gold ore mineral assemblage comparisons for this type of gold and copper ore outside the SMD. However, at least three stages of sulphide mineralisation were shown in this study to contain gold that is hosted predominantly by copper skarn assemblages in the SMD copper deposits located proximally to the SMD SHGD, namely SMD Stages 3B, 3C and 4A that are described in Chapter 5 (Section 5.8) and Chapter 6. The principal findings about gold occurrence in the SMD SHGD compared to the proximal copper skarn zones and the porphyry Cu-Mo centres are revisited here for discussion purposes from Chapter 5, (Section 5.8):

1. The SMD Stage 3B mineral assemblage group shows a decrease in gold grades from the distal to the central deposit settings, with (a) low-grades of gold in both SHGD Stage 3B pyrite and sphalerite in the distal SHGD deposits (<3 ppm Au), (b) less gold in SKN Stage 3B (Pyrite SKN1) in the proximal Cu skarn deposits (<0.4 ppm Au) and (c) only traces of gold present in Porphyry Stage 3B pyrite in the central porphyry type Cu-Mo deposits (<0.13 ppm Au).

2. The SMD Stage 3C contains chalcopyrite with inclusions containing low values of gold ranging from 0.06 to 0.9 ppm Au in association with Pb-Bi-As-Te at both the SMD central porphyry Cu-Mo and proximal Cu skarn settings, but the distal SMD SHGD mainly contained Cu-Sb-As sulphosalts.
The SMD Stage 4A main gold ore phase contains pyrite with high grades of gold ranging from >1 up to 293 ppm Au concentrated along (a) the growth rims of Pyrites 4A1 to 4A4 cores that in turn occur as pyrite grains along fractures cutting SMD Stage 3 sulphides in the SMD SHGD or (b) associated with rough textured Pyrite SKN2 cutting earlier copper-bearing SMD Stage 3C assemblages in the proximal Cu copper skarn setting.

Overall, the gold mineralogy and trace element associations indicate that SMD Stage 4A pyrite in both the SMD distal SHGD and the proximal Cu skarn deposits are similar in gold grades and also contain high levels of arsenic. This also suggests that SMD Stage 4A is a widespread mineralisation stage occurring in both deposit settings where it cuts and overprints fractures developed in earlier copper-bearing skarn assemblages throughout the SMD.

High-grade gold ore mineral assemblages with Carlin-type ore features located proximally to skarn and porphyry Cu-Mo-Au deposits are more akin to those of the DDGD type (Sillitoe and Bonham, 1990; John et al., 2003; Cunningham et al., 2004; Sillitoe, 2004; Johnson and Ressel, 2004; Cline et al., 2005). The principal examples of DDGD type include (a) Melco, Mercur and Barneys Canyon, Bingham porphyry district, Utah (Presnell and Parry, 1996; Gunter and Austin, 1997; Cunningham et al., 2004), (b) the Battle Mountain, Bullion, Marigold, Cove and McCoy deposits, Nevada, USA (Sillitoe and Bonham, 1990; Resssel et al., 2000; Johnston and Ressel, 2004; Johnston et al., 2008), (c) Mesel, Indonesia (Turner et al., 1994, Garwin et al., 1995), (d) Bau, Malaysia (Percival et al., 1990; Sillitoe and Bonham, 1990), and, (e) Yauricocha district, Peru (Table 8.3; Alvarez and Noble, 1988). The main characteristics of the DDGD type include (a) exhibiting similar ore mineral assemblages to the Carlin-type gold deposits, but mainly are an association with both sedimentary rocks and non-reduced intrusions, (b) having higher concentrations of base metals and silver, and (c) commonly appearing to be spatially and genetically associated with porphyry Cu-Mo-Au systems (Sillitoe and Bonham, 1990; Johnson and Ressel, 2004; Cline et al., 2005). Table 8.3 provides a comparison of the broad SMD mineralisation characteristics with other known districts hosting DDGD that are in association with skarn and/or porphyry Cu-Mo-Au deposits.

8.3.5 SMD gold ore summary

The mineral assemblages present in the SMD SHGD share several broad characteristics with those in the Nevada and Dian-Qian-Gui Carlin-type gold deposits and also some with the DDGD types (Tables 8.2 and 8.3). In particular, the SMD SHGD main gold ore stage commonly exhibits similarities to the Nevada and Dian-Qian-Gui Carlin-type gold deposits through (a) the presence of high concentrations of gold in arsenic-enriched pyrite overgrowths along the rims of SMD Stage 4A pyrite types, and (b) the occurrence of high grade gold in both SMD Stage 4A quartz replacement zones (jasperoid) and decarbonatised carbonate units.
Table 8.3. Comparison of the SMD main mineral groups and deposit settings with other known mineral districts containing distal-disseminated gold deposits (DDGD), skarn (Zn-Pb, Cu\textsuperscript{+}Au) and porphyry (Cu-Mo\textsuperscript{+}Au) deposits.

<table>
<thead>
<tr>
<th>District</th>
<th>Porphyry-type (alteration / mineralisation)</th>
<th>Skarn-type (alteration / mineralisation)</th>
<th>Age (intrusion)</th>
<th>DDGD-type (Au) (spatial association)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMD (Laos)</td>
<td>K-silicate and sericite altered rhyodacite porphyry stocks/Cu-Mo</td>
<td>Proximal calc-silicate skarn (Cu-Au\textsuperscript{+}Zn-Pb)</td>
<td>287 - 282 Ma</td>
<td>Adjacent ~ 1 km from Khanong Cu skarn deposit</td>
<td>2, 3, 4, 5, 6, 7, 8</td>
</tr>
<tr>
<td>Bingham (Utah, USA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bingham</td>
<td>K-silicate/Cu-Mo</td>
<td>Proximal carbonate replacement (Zn-Pb)</td>
<td>38 - 33 Ma</td>
<td>Adjacent deposits of Melco and Barneys Canyon</td>
<td>1, 14</td>
</tr>
<tr>
<td>Bingham</td>
<td>K-silicate/Cu-Mo</td>
<td>Proximal carbonate replacement (Zn-Pb)</td>
<td>38 - 33 Ma</td>
<td>Adjacent deposits of Melco and Barneys Canyon</td>
<td>1, 14</td>
</tr>
<tr>
<td>Melco</td>
<td></td>
<td></td>
<td></td>
<td>Adjacent ~ 6 km north of Bingham</td>
<td>12, 14</td>
</tr>
<tr>
<td>Barneys Canyon</td>
<td></td>
<td></td>
<td></td>
<td>Adjacent ~ 7 km north of Bingham</td>
<td>1, 13, 14</td>
</tr>
<tr>
<td>Nevada (USA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Railroad (Bullion)</td>
<td>K-silicate/Minor Cu-Mo</td>
<td>Proximal (Cu-Au) skarn and distal carbonate replacement (Zn-Pb)</td>
<td>35 - 37 Ma</td>
<td>Adjacent ~ 7 km distance from intrusion</td>
<td>1</td>
</tr>
<tr>
<td>Goldstrke</td>
<td></td>
<td></td>
<td></td>
<td>Jurass - Cretaceous</td>
<td>15</td>
</tr>
<tr>
<td>Battle Mountain</td>
<td>K-silicate/Minor Cu-Mo</td>
<td>Proximal (Cu-Au) skarn and distal Au-A-(Pb-Zn)</td>
<td>38.5 Ma</td>
<td>Adjacent to intrusion</td>
<td>1</td>
</tr>
<tr>
<td>Gold Acres</td>
<td>K-silicate (biotite)</td>
<td>Mo-Cu-Zn skarn</td>
<td>93 - 99 Ma (skarn)</td>
<td>Overprinted and above</td>
<td>1</td>
</tr>
<tr>
<td>Getchell</td>
<td></td>
<td>W-(Mo) skarn</td>
<td>88 - 92 Ma (skarn)</td>
<td>Adjacent</td>
<td>1, 9</td>
</tr>
<tr>
<td>McCoy</td>
<td></td>
<td>Zn-Pb skarn</td>
<td>39 Ma</td>
<td>Overprinted and adjacent to intrusion</td>
<td>10, 11</td>
</tr>
<tr>
<td>Bau (Malaysia)</td>
<td>K-silicate and sericite altered microgranodiorite and dacite stocks / Minor Cu-Mo-Au+ (Pb-Zn-Sb)</td>
<td>Calc-silicate skarn/W and trace Cu, No Au</td>
<td>Miocene</td>
<td>Adjacent and distal from intrusion</td>
<td>1, 16</td>
</tr>
<tr>
<td>Mesel (Indonesia)</td>
<td>Sericite altered andesite / No mineralisation reported</td>
<td></td>
<td>11.2 - 13.9 Ma</td>
<td>Adjacent and below intrusion</td>
<td>1, 17</td>
</tr>
<tr>
<td>Kyaukpahto (Myanmar)</td>
<td></td>
<td>Cretaceous</td>
<td></td>
<td>Adjacent and distal from intrusion</td>
<td>19</td>
</tr>
<tr>
<td>Yauricocha (Peru)</td>
<td>K-silicate altered granodiorite stock</td>
<td>Proximal carbonate replacement (Zn-Pb)</td>
<td>Late Miocene</td>
<td>Adjacent and distal from intrusion</td>
<td>1, 18</td>
</tr>
</tbody>
</table>

However, the occurrence of low grade gold-bearing base metal veins in SMD Stages 3B and 3C main gold ore stage cutting both RDP and carbonate rock types is probably more typical of the DDGD-type (Table 8.2). Examples of gold deposits in Nevada containing both centrally positioned DDGD-type base metal-dominant gold ore zones hosted by felsic intrusions, and proximal disseminated pyrite dominant Carlin-type gold ore zones hosted by calcareous sedimentary rocks include both the Cove and McCoy deposits described by Johnston et al. (2008). Overall, the presence of high gold grade arsenic-rich zoned pyrite types in both the SMD SHGD and Cu skarn deposits (i.e. Pyrites 4A1-4A4 and -SKN2) cutting earlier primary base metal sulphides (SMD Stages 3B and 3C) is more similar to main gold ore primary sulphide-bearing mineral assemblages occurring in zoned mineral districts containing both distal Carlin-type and DDGD type deposits peripheral to proximal base metal skarn (Zn-Pb+Cu) deposits and/or porphyry Cu-Mo deposits (Table 8.3).

### 8.3.6 Timing of SMD Au and Cu mineralisation

A wide range of ages from the Palaeozoic to the Tertiary are reported for gold occurring in Carlin-type and DDGD-type gold districts worldwide (Kerrich et al., 2000; Hofstra and Cline, 2000; Emsbo et al., 2003; Cunningham et al., 2004; Cline et al., 2005; Emsbo et al., 2006; Peters et al., 2007). Some districts hosting Carlin-type gold deposits have complex histories that have resulted in multiple gold-mineralising events producing several deposit styles (Hofstra and Cline, 2000; Emsbo et al., 2003; Cline et al., 2005; Emsbo et al., 2006). In particular, the Great Basin in Nevada hosts multiple gold deposits of different ages, e.g.: (a) Devonian-aged SEDEX base metal deposits containing up to 68 ppm Au at the Rodeo deposit, (b) Late Jurassic felsic stocks (160-158 Ma) with base metal veins containing between 5 to 100 ppm Au in the Goldstrike Stock and also at the Cortez deposit, (c) the age of post-mineralisation Middle Tertiary (Eocene) porphyry dikes and main gold stage gahkhlite constrain the formation of the high-grade Carlin-type gold ores at the Getchell deposit to between 36 to 42 Ma, and (d) Miocene epithermal systems (Hofstra and Cline, 2000; Emsbo et al., 2003; Cline et al., 2005; Emsbo et al., 2006).

The ages of gold mineralisation in the Dian-Qian-Gui Carlin-type gold deposits in southern China are poorly constrained, but are interpreted to contain gold deposited during the Cretaceous (Late Yanshanian) to Early Tertiary (Kerrich et al., 2000; Zhang et al., 2003; Peters et al., 2007). Lead isotope dating of galena and gold-bearing pyrite occurring along extensional faults yielded 100 Ma ages for samples from the Yata, Banqi and Sanchahe Carlin-type gold deposits in Guizhou Province, Dian-Qian-Gui region (Ashley et al., 1991, Zhang et al., 2003). Furthermore, the U-Pb dating of samples interpreted to be syn- to post-gold mineralisation from the Carlin-type gold deposits in Guizhou Province yielded 20 to 60 Ma ages (Zhang et al., 2003). The Chuan-Shan-Gan district in north-central China is reported to contain Carlin-type
gold mineralisation formed during the Early to Middle Mesozoic (Li and Peters, 1998; Wang et al., 1999; Kerrich et al., 2000; Mao et al., 2002). Overall, the ages of Carlin-type gold mineralisation in Nevada and China are not the same, but the Eocene period in Nevada is recognised for the formation of the known large tonnage Carlin-type gold deposits (Kerrich et al., 2000; Hofstra and Cline, 2000; Cline et al., 2005; Emsbo et al., 2006).

Multiple gold-mineralising events are likely to have occurred in the SMD, based on the sulphide mineral paragenesis observations described in Chapters 5 and 6. At least four gold-bearing sulphide stages have been documented in this study, namely SMD Stages 2B, 3B, 3C and 4A. The paragenetically early pre-main gold ore stage SMD pyrite generations contain the lowest concentrations of gold, namely Pyrite 2B (SMD Stage 2), Pyrite 3B and Pyrite SKN1 (SMD Stage 3B) and Chalcopyrite 3C (SMD Stage 3C; Chapter 6, Table 6.2.6). The later main gold ore stage SMD pyrites contain the highest gold concentrations in Pyrites 4A1-4A4 and Pyrite SKN1 (SMD Stage 4A; Chapter 6, Table 6.2.6). The key findings are summarised here in order of paragenetic timing interpreted from the oldest to the youngest stages:

1. **Devonian to Early Permian:** Pyrite 2B (SMD Stage 2B) is one of the earliest formed SMD pyrite types in the SMD SHGD containing very low gold levels (i.e. <0.5 ppm Au), mostly concentrated in the pyrite cores. Pyrite 2B is mainly hosted by the Middle Devonian Discovery Formation and is interpreted to have formed during diagenesis before emplacement of the Early Permian RDP intrusions into the SMD.

2. **Early Permian (297 to 287 Ma):** Pyrite 3B associated with the SMD Stage 3B base metal veins cutting both RDP and carbonate rocks in the distal SHGD contained low levels of up to 1.8 ppm Au, mainly occurring as inclusions. Moreover, RDP and carbonate rocks cut by veins with SMD Stage 3B Pyrite SKN1 associated with proximal skarn assemblages in the SMD copper deposits also contain low levels of Au, up to 0.7 ppm, and mainly occurring as small inclusions. The SMD RDP intrusions hosting the SMD Stage 3B base metal veins contain zircons that were U-Pb dated in this study as Early Permian (i.e. 297 to 280 Ma; Chapter 3).

3. **Early Permian (287 to 280 Ma):** Chalcopyrite 3C from the SMD Stage 3C proximal skarn mineral assemblage in the SMD copper deposits contains low levels of Au (up to 0.9 ppm) as small inclusions. Chalcopyrite 3C was observed to fill fractures in earlier Pyrite SKN1 (SMD Stage 3B) and is also coeval with molybdenite in the SMD Stage 3C retrograde porphyry and skarn assemblages at both Padan and Thengkham respectively. The timing of the SMD Stage 3C retrograde skarn hypogene copper-molybdenite mineralisation was constrained during this study by Re-Os dating to a 7 Ma period between 287.2 ± 1 Ma to 280.2 ± 1 Ma (Chapter 5).

4. **Syn- to post-Early Permian (<280 Ma):** The highest concentrations of gold ranging from >1 and up to 293 ppm predominantly resided in the pyrite overgrowth rims of SMD Stage 4A main gold ore stage pyrite types, namely Pyrites 4A1 to 4A4 and Pyrite SKN1 (Chapter 6, Table 6.2.6). Although the age of SMD Stage 4A gold mineralisation in the SMD SHGD remains unconstrained, it does however clearly cut the earlier SMD Stage 3C mineral assemblages at the Khanong and Discovery East deposits and is therefore younger than the 287 to 280 Ma formation of SMD Stage 3C molybdenite and chalcopyrite (i.e. Chalcopyrite 3C).
8.4 TRACE ELEMENT, FLUID AND ISOTOPE GEOCHEMISTRY

8.4.1 Trace elements

The LA-ICPMS and PIXE trace element studies presented in Chapter 6 established that gold occurs in all of the SMD pyrite types investigated, commencing with low concentrations of gold (<0.5 to 3 ppm Au) in the paragenetically early pre-main gold ore stage pyrite generations, namely Pyrite 2B (SMD Stage 2), Pyrite 3B and Pyrite SKN1 (SMD Stage 3B) and Chalcopyrite 3C (SMD Stage 3C). The highest gold concentrations ranging from >3 up to 293 ppm Au occur later in main gold ore stage Pyrite 4A and Pyrite SKN1 (SMD Stage 4A). Each of the pyrite types investigated displayed distinctive trace element associations which also varied between the SMD SHGD and those in the proximal copper skarn zones in the SMD copper deposits (Chapter 6, Section 6.2). The characteristics of the SMD trace element associations compared with those occurring in known gold systems and where possible, the source of trace elements is discussed in order of paragenesis.

8.4.1.1 Trace elements: Source of metals

Pyrite 2B (SMD Stage 2) is diagenetic and the earliest formed pyrite type in the SMD. It is predominantly hosted by Middle Devonian Discovery Formation calcareous shale, was only observed in the SMD SHGD, and typically contains Pb-Ni-Co-As-Ti towards the pyrite cores, together with traces of up to 0.5 ppm Au. In comparison, Zhang et al. (2005) report that diagenetic pyrite occurring in the stratigraphy hosting some of the Carlin-type gold deposits in the Dian-Qian-Gui region in southern China also contained elevated levels of Co, Ni and Pb. Moreover, the rims of Pyrite 2B all displayed lower levels of gold (<0.2 ppm), which are similar to associations observed by Wood and Large (2007) who report that diagenetic pyrite in western Victoria, Australia, are enriched in gold in their cores and have low levels of gold in their rims, implying that likely accumulation of syngenetic or syndiagenetic gold during pyrite formation. Furthermore, the SMD Pyrite 2B second order of trace element associations ranging in concentrations from >10 ppm to <100 ppm include Cr-Zn-Sb-Mn-Se-Ba-Te and the third order of trace elements (<10ppm) contained V-Bi-Mo-Ag-Sn-Tl-W, similar to the trace elements described by Large et al. (2007) that are concentrated by organic processes in euxinic sedimentary environments. Based on these observations, but only on a limited data set of four samples, it is plausible that Pyrite 2B also formed under reduced conditions in the Sepon Basin and contains syngenetic or syndiagenetic concentrations of gold (up to 0.5 ppm), hence providing a potential protore sedimentary source of very low grade gold in the SMD.

The second generation of pyrites comprise Pyrite SKN1 and Pyrite 3B, both occurring in the SMD Stage 3B pre-main gold and pre-main copper ore assemblages and hosted by veins cutting carbonate rocks and RDP intrusions (Chapter 5). Pyrite SKN1 is associated with the proximal early retrograde skarn mineral assemblages in the SMD copper deposits and typically consists of a first order of Cu-Co-Se-Ni-Bi-Mn-Te (>100 ppm concentrations) and second order As-Mo-Pb-Ag-V-W-Ti (>10 to <100ppm concentrations) and also concentrations of up to 0.7
ppm Au. Pyrite 3B occurs in the more distal SMD SHGD and mainly contains a primary order of As-Cu-Ni-Pb, secondary order Se-Zn-Sb-Co and concentrations of up to 1.8 ppm Au. In comparison, Pyrite SKN 1 contains higher levels of Zn, Co, Se, Bi, Mn, Te and V and lower levels of As, Pb and Au when compared to Pyrite 3B. The predominance of Se, Bi and Te in Pyrite SKN 1 is possibly indicative of derivation from a magmatic source according to similar observations of these trace elements formed by magmatic hydrothermal processes in volcanic-hosted massive sulphide systems (VHMS) with Cu-rich zones reported by Huston et al. (1995) and also in the intrusion-related gold systems described by Thompson and Newberry (2000).

Chalcopyrite 3C (SMD Stage 3C) is the third generation of pyrite containing gold in the SMD, but is only observed in the proximal late retrograde skarn mineral assemblages cutting both RDP and carbonate rocks at the copper deposits (Chapter 5). Chalcopyrite 3C is also one of the main sources of hypogene copper in the SMD and consists of a first order association of Cu-Zn-Se-Bi (>100 ppm concentrations), second order of Sn-Ag-Pb-Mo-V-Ti-As-Te (>10 to <100 ppm concentrations) and also minor inclusions of Au (<0.9 ppm Au). In addition to the elevated levels of Se and Bi, high levels of Sn and Mo also occur in Chalcopyrite 3C when compared to Pyrite SKN 1. Taking into consideration that Chalcopyrite 3C is hosted by veins cutting RDP intrusions, has magmatic $\delta^{34}$S values (Chapter 7), and also contains associations of Se, Bi, Sn and Mo, a magmatic source is likely for this pyrite type.

The fourth generation of pyrite hosts high grades of up to 293 ppm Au in Pyrite 4A (comprising types 4A1 to 4A4) and Pyrite SKN2 that are both classified with the main gold ore assemblages in the SMD (Chapter 5). Pyrite 4A predominantly occurs in the SMD SHGD, is hosted mainly by calcareous shale, but also occurs in fracture zones cutting dolomite and RDP intrusions. Pyrite 4A contains high gold values of up to 200 ppm Au that characteristically occurs in pyrite overgrowths on the rims of earlier pyrite generations and in close association with a first order trace element association comprising As-Sb-Pb-Cu-Ni-Ti-Zn-Mn-Ag-Tl (>100 ppm concentrations) and second order association of Co-Te-Se-Ba-Cr-Bi (>10 to <100 ppm concentrations). This first order trace element suite for Pyrite 4A is very similar to that reported by Zhang et al. (2005) at the Zimudang Carlin-type gold deposit in the Dian-Qian-Gui region, China. The major trace element associations at most of the Carlin-type gold deposits in the Dian-Qian-Gui region, southern China are commonly As-Sb-Tl-Cu-Hg, which are similar to those observed in Pyrite 4A (Hu et al., 2002; Zhang et al., 2005; Peters et al., 2007).

The trace element associations with the high grades of gold that are predominantly concentrated along the rims of main gold stage pyrite at the Nevada Carlin-type gold deposits are typically As-Sb-Tl-Hg-Ag-Te-W, but they also have low amounts of Mo, Cu, Zn, Pb, Bi, Mn, Ni and Co (Hofstra and Cline, 2000; Cline et al., 2005). Sulphidation processes are inferred for the concentration of these elements on pre-existing pyrite cores (Hofstra and Cline, 2000). Pyrite 4A appears to have similar associations of As-Sb-Tl-Ag with gold but also has elevated levels of Pb, Zn, Ni, Mn and Ti when compared to those in the Nevada Carlin-type gold deposits. This is interpreted to reflect the local sourcing of these elements from pre-existing base metal sulphides in which Pyrite 4A occupies fractures that often cut SMD Stage
3A and 3B base metal veins, in particular for Pb and Zn and also from the surrounding sedimentary host rocks for Ti, Mn and Ni. Hofstra and Cline (2000) report that low temperature ore fluids (<250°C) with high H₂S concentrations potentially have high trace element concentrations, high Au/Ag ratios and low base metal concentrations due to H₂S enhancing the solubility of Au, As, Sb, Tl and Hg but suppressing the solubility of Fe, Ag and base metals as chloride complexes. At temperatures >200°C, processes of adsorption or co-precipitation of sulphide complexed trace elements at sulphur sites in iron sulphides are more dominant than for chloride or other complexes, in particular for As, Sb, Tl, Hg and base metals (Hofstra and Cline, 2000 and references therein). Based on these observations, it is plausible that Pyrite 4A also formed by process involving H₂S due to quartz associated with this pyrite type yielding relatively high minimum homogenisation temperatures ranging from 180°C to 290°C, but this hypothesis currently remains unconstrained due to the poor gas yields from fluid inclusions during Laser Raman Spectrometry studies to confirm the presence of H₂S.

Additionally, the Nevada Carlin-type gold deposits commonly have Au/Ag ratios >10, indicating that high levels of Au relative to Ag deposited during gold-ore formation. Although the intrusion-related DDGD have several characteristics similar to the Carlin-type gold deposits, they differ in having higher Ag and base metal concentrations (Cline et al., 2005). The Au/Ag ratio determined for Pyrite 4A is 1.29, indicating that higher levels of Ag deposited during gold ore formation in the SMD and are more similar to those described for the DDGD-types.

Pyrite SKN2 is also a SMD Stage 4A high grade gold-bearing pyrite containing >1 to 293 ppm Au. It predominantly cuts the earlier proximal copper skarn SMD Stage 3 group mineral assemblages in the SMD copper deposits. Gold in Pyrite SKN2 is closely associated with a first order trace element association of Cu-As-Bi-Fe-Se-Pb-Zn-Ag (>100 ppm concentrations) and a second order of Te-Sb-Ni-Sn-Mo (>10 to <100 ppm concentrations). This pyrite type contains higher levels of Bi, Cu, Co, Se, Sn and Mo and lower levels of As, Sb and Tl when compared to Pyrite 4A from the SMD SHGD. Moreover, the elevated levels of Bi, Cu, Se, Sn and Mo in Pyrite SKN2 are also similar to the trace elements occurring in magmatic systems, in particular the intrusion-related gold systems (Thompson and Newberry, 2000).

Overall, it is interpreted that the high-grade gold-bearing SMD Stage 4A pyrite types may be locally sourcing trace elements from (a) the surrounding sedimentary rocks through the inclusion of Ti, Mn and Ni in the Pyrite 4A types at the SMD SHGD, and (b) also from a magmatic intrusion-related source as indicated by the presence of elevated Bi, Cu, Ag, Se and Sn in Pyrite SKN1 at the proximal copper skarn zones. Over time, gold grades increase in all the younger generations of pyrite types. Opportunity to provide additional iron sulphide nucleation sites to enable formation of the later high-grade gold-bearing Pyrite 4A types appears to be enhanced after the emplacement of base metal veins from the SMD Stages 3B and 3C assemblages. Furthermore, it is also possible that gold could potentially be sourced from both the early SMD Stage 2 diagenetic pyrites and also from the later SMD Stage 3B and 3C pyrite types syn- to post-emplacement of the SMD RDP intrusions.
8.4.1.2 Trace element spatial distribution: SMD gold and copper deposits

Previous surface stream geochemical observations discussed in Manini et al. (2001) and references therein describe anomalous trace element zoning in the SMD consisting of (a) Cu-Mo at the RDP porphyry centres, (b) Cu-Au predominantly at the proximal skarns surrounding RDP porphyry centres, and (c) Au occurring both distally and adjacent to proximal skarn zones, as previously represented in Fig. 1.4, Chapter 1. In this study, trace element investigations of sulphide minerals collected from the hypogene zones at the various SMD gold and copper deposits confirm these earlier observations from Manini et al. (2001). Moreover, the trace element studies presented in Chapter 6 indicate the following spatial distribution of characteristic trace elements identified at the following deposit types: (a) Cu-Bi-Se ± Au-Mo in the proximal skarn zones at the SMD copper deposits, and (b) Au-As-Ag-Sb-Se-Tl ± Cu-Pb-Zn at the SMD SHGD from the Nalou to Discovery East deposits and Au-As-Sb ± Cu-Bi at the Phavat deposit (Fig. 8.1). Associations of Au-As-Ag-Sb-Tl are more prominent in calcareous shale and carbonate rocks hosting the SMD SHGD compared to Cu-Bi-Se being more pronounced in the proximal skarn zone settings at the SMD copper deposits that are mainly hosted by both carbonate rock and RDP intrusions (Fig. 8.1).

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Fig. 8.1. Schematic diagram showing a simplified long section interpretation of the SMD geology and the spatial distribution of (a) the characteristic trace element patterns, and (b) the associated sulphur isotope values for each mineral stage for the gold and copper deposit types in the SMD. *Abbreviations used:* SHGD = sedimentary rock-hosted gold deposit, SKN = skarn, ST = paragenetic stage, PY = pyrite, RDP = rhyodacite porphyry intrusion, DSE = Discovery East (SHGD), KHN = Khanong copper deposit, NLU = Nalou (SHGD), TKM = Thengkham South copper deposit, TKN = Thengkham North copper deposit, VAT = Phavat (SHGD), CHE = chert, CSH = calcareous shale, DOL = bioclastic dolomite, SLT = siltstone, SST = sandstone, NMK FM = Nam Kian Formation, DIS FM = Discovery Formation, NLU FM = Nalou Formation, KGK FM = Kengkeuk Formation, VNG = Vang Ngang Formation, NPA = Nampa Formation.
8.4.2 Fluid chemistry

The SMD fluid inclusion studies and the oxygen and hydrogen isotope analyses presented in Chapter 7 previously compared the results with other known deposit types (Sections 7.1 and 7.2 respectively). This section summarises in order of paragenesis the main characteristics and the potential sources of the SMD copper and gold ore fluids. The comparative fluid chemistry data is also summarised in Table 8.4.

8.4.2.1 Ore-fluid homogenisation temperatures

The SMD fluid inclusion data indicate that zoning from hotter to cooler mineralising fluids occurs between deposit types in the SMD, in particular the pre-main gold SMD Stage 3B quartz generation associated with early base metal veins has homogenisation temperatures (Th) with: (a) high temperatures ranging from 250 to 325°C in RDP intrusion quartz phenocrysts at the central Padan porphyry (Cu-Mo) Prospect; (b) low-moderate temperatures from 190 to 205°C in the proximal skarn zones at the SMD copper deposits, and (c) moderate temperatures from 190 to 290°C at the adjacent to distal SMD SHGD. The retrograde SMD Stage 3C quartz (pre-main gold ore, but also main copper ore stage) with Chalcopyrite 3C contains low-moderate homogenisation temperatures ranging from 175 to 260°C at both the Padan porphyry Cu-Mo Prospect and also in the proximal skarn zones at the Khanong and Thengkham South copper deposits. These temperatures occur within the lower limits of those described by Wilson et al. (2002) for low-temperature late ore stage magmatic fluids in porphyry copper deposits that range from 200 to 350°C. Although the SMD Stage 3 copper-bearing ore fluids have Th values less than 350°C, copper is interpreted to be transported at these temperatures as oxidised fluids that become reduced at the trap site, under the conditions described by Huston et al. (1998). Furthermore, the presence of minor primary hematite associated with the SMD Stage 3C mineral assemblage suggests that the copper-bearing ore fluids were oxidised and could possibly form at temperatures <350°C.

The main gold ore SMD Stage 4A quartz associated with high grade gold-bearing pyrite (Pyrites 4A1 to 4A4) in the SMD SHGD has a wide distribution of ore fluid Th values ranging from 180 to 290°C with populations clustering at 180 to 210°C and 230 to 290°C (Table 8.4). The SMD Stage 4A main gold ore stage mineralising fluids occurring in the SMD SHGD are also comparable to those in the Dian-Qian-Gui Carlin-type gold deposits, China with Th values predominantly ranging from 165 to 290°C and up to 327°C (Ashley et al., 1991; Cromie and Khin Zaw, 2003; Peters et al., 2007). Furthermore, polymetallic veins containing base metals and associated gold at the Cove DDGD-type deposit are also reported to contain moderate to high Th values in quartz ranging from 210 to 370°C (Johnston et al., 2008). However, the Th values from both the SMD SHGD and the Dian-Qian-Gui Carlin-type deposit studied so far generally have hotter gold-ore stage ore fluids than those in the classical Nevada Carlin-type gold deposits that typically range from 140 to 240°C as described by Cline et al.
(2005). In comparison, the SMD Stage 4A main gold ore Th values also occur within the known ranges reported for the SEDEX Au type brine and low sulphidation epithermal models, but are more similar to those described for the Phanerozoic orogenic Au amagmatic metamorphic fluid, distal-disseminated Au magmatic, and low-temperature porphyry Cu-Au magmatic models (Table 8.4).

8.4.2.2 Ore-fluid salinities

Fluid inclusions in pre-main gold ore SMD Stage 3C quartz associated with retrograde main copper ore mineralisation (i.e. Chalcopyrite 3C) at both (a) the SMD copper deposits at Khanong and Thengkham South and (b) the Padan porphyry Cu-Mo Prospect, show similar distinct tight and overlapping moderate salinity values ranging from 7.7 to 11.2 wt % NaCl equiv. and 5.9 to 9.1 wt % NaCl equiv. respectively (Chapter 7, Section 7.1). In comparison, the salinity data for the copper-bearing ore fluids in SMD Stage 3C quartz are similar to the moderate to high salinities reported for magmatic systems, in particular the late-stage low temperature fluids in porphyry (Cu) systems (Wilson et al., 2002) and also the ore fluids in high sulphidation epithermal deposits (Cooke and Simmons, 2000).

The main gold ore SMD Stage 4A quartz associated with high-grade gold in Pyrites 4A1 to 4A4 at the SMD SHGD also contains moderately saline fluids and comprise at least two populations of salinity values ranging from 4.3 to 8.6 wt % NaCl equiv. and 12.1 to 13.7 wt % NaCl equiv., indicating the presence of two fluids during gold ore formation (Table 8.4). Salinity data reported by Cromie and Khin Zaw (2003) from the Fu Ning Carlin-type gold deposits in the Dian-Qian-Gui, China also indicated that there were two fluids present during gold deposition, comprising (1) an early low to moderate salinity fluid with 0.8-6.5 wt % NaCl equiv., comparable to the salinities in shear zone-hosted gold deposits containing metamorphic fluids as described Groves et al. (1998), and (2) a late stage moderately high salinity fluid with 11.8-13.4 wt % NaCl equiv., indicating possible salinity derived from brine or magmatic sources as discussed by Emsbo et al. (2003) and Sillitoe and Bonham (1990) respectively. The presence of two ore fluids having both low and moderate salinities suggests processes of fluid mixing during gold mineralisation that have been described for some of the Nevada Carlin-type gold deposits during studies by Osterberg (1990), Kuehn and Rose (1995), Arehart (1996) and in discussions by Hofstra and Cline (2000) and Cline et al. (2005). Additionally, evolved meteoric waters containing up to 8 wt % NaCl equiv. are also reported in some of the Nevada Carlin-type gold deposits (Hofstra, 1997; Hofstra and Cline, 2000). The two fluids detected in SMD Stage 4A quartz are more consistent with (1) metamorphic and/or evolved meteoric fluids for those with low-moderate salinities <9 wt % NaCl equiv. and (b) both magmatic and/or basinal brine origins for fluids comprising moderate-high salinities with >9 wt% NaCl equiv. (Table 8.4).
Table 8.4. Comparison of fluid chemistry and sulphur isotope data from the SMD gold and copper deposits with other genetic models.

<table>
<thead>
<tr>
<th>Type</th>
<th>Th (°C)</th>
<th>Wt % (NaCl eq.)</th>
<th>Gases</th>
<th>Fluids</th>
<th>δ³⁴S</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SMD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHGD (SMD Stage 4A)</td>
<td>180 to 290</td>
<td>&gt;4 to &lt;14</td>
<td>No results</td>
<td>Not constrained</td>
<td>-28 to -2</td>
<td>This study</td>
</tr>
<tr>
<td>Skarn Cu (SMD Stage 3C)</td>
<td>175 to 255</td>
<td>&gt;7 to &lt;12</td>
<td>CO₂ (variable)</td>
<td>Not constrained</td>
<td>-2 to +2</td>
<td>This study</td>
</tr>
<tr>
<td>Porphyry Cu-Mo (SMD Stage 3C)</td>
<td>255 to 325</td>
<td>&gt;5 to 9</td>
<td>CO₂ (variable)</td>
<td>Not constrained</td>
<td>-13 to -0.5</td>
<td>This study</td>
</tr>
<tr>
<td><strong>Magmatic</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DDGD Au</td>
<td>200 to 400</td>
<td>&gt;10</td>
<td>CO₂ (variable) acidic to neutral</td>
<td>H₂S (variable)</td>
<td>15 to +4</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>Porphyry Cu-Mo-Au (low temperature)</td>
<td>200 to 350</td>
<td>&lt;10</td>
<td>SO₂ (high) acidic to neutral (Oxidised)</td>
<td></td>
<td>-5 to +3</td>
<td>4</td>
</tr>
<tr>
<td>(high temperature)</td>
<td>300 to &gt;600</td>
<td>&gt;30</td>
<td>SO₂ (high) acidic to neutral (Oxidised)</td>
<td></td>
<td>-5 to +3</td>
<td>4</td>
</tr>
<tr>
<td><strong>Metamorphic</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orogenic Au</td>
<td>200 to &gt;350</td>
<td>0.5 to 5</td>
<td>CO₂ (high) near neutral (reduced)</td>
<td></td>
<td>0 to +10</td>
<td>2, 5</td>
</tr>
<tr>
<td><strong>Meteoric</strong></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Epithermal Au (Low Sulphidation)</td>
<td>100 to 300</td>
<td>1 to 3</td>
<td>H₂S (high) near neutral (reduced)</td>
<td>CO₂ (low)</td>
<td>-10 to 0</td>
<td>6</td>
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<tr>
<td><strong>Brine</strong></td>
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<td></td>
</tr>
<tr>
<td>SEDEX Au</td>
<td>190 to 280</td>
<td>9 to 22</td>
<td>H₂S (high) acidic to neutral (reduced)</td>
<td></td>
<td>-5 to 31</td>
<td>7</td>
</tr>
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</table>

8.4.2.3 Depths of ore deposition and fluid inclusion gas compositions

Fluid inclusion studies of the main gold stage ore fluids in the Nevada Carlin-type gold deposits are characterised by gases that generally contain <4 mol % CO₂, are poor in CH₄ (<0.4 mol %) and have moderate amounts of H₂S (10⁻¹ to 10⁻² mol %), inferring that some of these deposits were formed at depths ranging from 1.7 to 6.5 km (Arehart, 1996; Hofstra and Cline, 2000; Cline et al., 2005). However, geological reconstructions of the Alligator Ridge Carlin-type gold deposits in northern Nevada indicates that these gold deposits were formed at shallower depths of <300m to 800m (Nutt and Hofstra, 2003). Previous fluid inclusion studies of Carlin-type gold deposits in the Dian-Qian-Gui, South China also report a wide range of formation depths mostly between 300m and 1500m and up to 9.2 km (Hofstra et al., 2005; Peters et al., 2007).

Furthermore, the primary fluid inclusions associated with gold mineralisation in the Fu Ning Carlin-type gold deposits in the Dian-Qian-Gui, China, predominantly contained CO₂ with minor N₂ and trace CH₄. These results indicate that the Fu Ning gold deposits possibly formed at depths greater than 2 to 3 km, based upon the CO₂ criteria described by Arehart (1996); they also suggest that the fluid conditions were reduced due to the presence of detectable CH₄ (Cromie and Khin Zaw, 2003).

In comparison, based on the presently known stratigraphy, the SMD SHGD have probably formed at depths as shallow as <400m to >650m in the Discovery Formation calcareous shale, >650m to 800m in Nalou Formation bioclastic dolomite and down to >1250m depth in the Vang Ngang Formation siliciclastic rocks (Manini et al., 2001; Smith et al., 2005). The SMD copper deposits at Khanong and Thengkham South are positioned at stratigraphic depths as >650m to 800m in the Nalou Formation and down to at least >1250m in the Vang Ngang Formation (Loader, 1999; Cannell and Smith, 2008). Only trace CO₂ (>0.1 mol %) was detected in SMD Stage 3C quartz samples containing copper ore-stage chalcopyrite (i.e. Chalcopyrite 3C) from the Thengkham South copper deposit and the Padan porphyry Cu-Mo Prospect, suggesting possible formation at depths greater than >2km. However, these observations are inconclusive and have not been applied as depth related pressure correction estimates for the SMD homogenisation temperature (Th) data described in Chapter 7 and hence, are only considered to be minimum temperatures for both the gold and copper ore fluids.

8.4.2.4 Source of ore fluid components: Presence of CO₂ in fluid inclusions

Several deposit types are reported to contain CO₂ in ore fluids, indicating deep fluid origins, namely orogenic gold deposits (Groves et al., 1998; Mernagh et al., 2007), intrusion-related gold deposits (Baker, 2002) and at some of the Carlin-type gold deposits (Table 8.4; Arehart, 1996; Cline et al., 1997; Hofstra and Cline, 2000). Gold ore fluids in magmatic systems generally contain variable amounts of CO₂ and H₂S, but the highest concentrations of CO₂ are reported to occur in the metamorphic ore fluids that are associated with orogenic gold
deposits (Groves et al., 1998; Seedorff and Barton, 2004; Mernagh et al., 2007). The present SMD data set does not constrain the origins of CO₂ detected in both the gold and copper mineralising hydrothermal systems, but does suggest that some deeply sourced fluids of probable magmatic origins supported by evidence of magmatic sulphur isotope compositions are involved in the formation of the SMD copper-bearing fluids.

8.4.2.5 Source of ore fluid components: Oxygen and Hydrogen isotope studies

The oxygen isotope studies presented in Chapter 7 provide data on the δ¹⁸O compositions of pre-main gold ore-bearing fluids in quartz, with the calculated δ¹⁸O values from (a) SMD Stage 3B (i.e. Zn-Pb base metal veins) and (b) SMD Stage 3C (i.e. Chalcopyrite 3C, main-primary sulphide copper ore) occurring in the fields described by Rollinson (1996) and references therein for meteoric water, ranging from +0.9 to +1.8 ‰ (at 193 to 223°C) and -0.8 to +3.6 ‰ (185 to 237°C) respectively. Furthermore, although the bi-variate plot of the SMD δ¹⁸O and δD compositions presented in Chapter 7 is limited by only two data points, it indicates that the (a) SMD Stage 3B fluid reports in the field for metamorphic waters (Rollinson, 1996) and is also adjacent to the field for magmatic water described by Taylor (1974) and (b) SMD Stage 3C fluid occurs just outside the fields for both metamorphic and magmatic waters (Table 8.4).

The SMD Stage 4A main gold ore stage fluids in quartz associated with high-grade gold-bearing Pyrites 4A1 to 4A4 yielded δ¹⁸O values ranging from 9.3 to 13.8 ‰ calculated at 234°C and 260°C respectively, and are comparable to those occurring in the known fields for metamorphic and magmatic waters (Table 8.4). However, the associated δD compositions remain unconstrained due to the poor gas yields from fluid inclusions in this stage. By comparison, the oxygen and hydrogen isotope studies of the Nevada Carlin-type gold deposits also contain variable combinations of meteoric, magmatic and/or metamorphic waters in gold ore forming fluids, indicating that no one source of fluid is solely responsible for the formation of these deposit types (Cline et al., 1997; Hofstra and Cline, 2000; Emsbo et al., 2003; Cline et al., 2005). In general, the present SMD data indicate that (a) the δ¹⁸O and δD compositions from the SMD Stage 3B and 3C pre-main gold ore assemblages indicate ore fluid characteristics similar to metamorphic and/or magmatic waters, and (b) the SMD Stage 4A main gold ore stage fluids have δ¹⁸O values that also in the ranges for metamorphic and magmatic waters, although contributions from evolved meteoric waters cannot be ruled out.
8.4.3 Sulphur isotopes: Source of sulphur

Sulphur isotope studies identified at least three characteristic groups of $\delta^{34}S$ values, suggesting a variety of origins of sulphur occurring in the SMD. Discussions and comparisons of the SMD $\delta^{34}S$ values with other known deposits styles were previously presented in Chapter 7 and are also summarised in Table 8.4. The main SMD $\delta^{34}S$ groups are:

1) Sedimentary pyrite: Pre-main gold ore SMD Stage 2B diagenetic pyrite yielded a wide range of $\delta^{34}S$ values from -11.6 to +33‰ (Chapter 7). These results are comparable to the ranges of $\delta^{34}S$ values for sedimentary pyrite types described in Carlin-type gold deposits in Nevada, USA (Hofstra, 1997; Hofstra and Cline, 2000), and the Dian-Qian-Gui, Southern China (Zhang et al., 2005; Zhang et al., 2003; Cromie and Khin Zaw, 2003; Li and Peters, 1998; Peters et al., 2007).

2) RDP intrusion associated base metal sulphides: In contrast, the pre-main gold ore SMD Stage 3 group of base metal sulphides comprising pyrite, sphalerite and galena at the SMD SHGD and chalcopyrite at the SMD copper deposits have $\delta^{34}S$ values that are mainly centred on 0‰ and ranging from -6.3 to +8.2‰. These $\delta^{34}S$ values, in particular those for SMD Stage 3C chalcopyrite (i.e. main primary copper ore) are more similar to those described for (a) deep magmatic sources with values also centred on 0±5‰ (Hofstra, 1997; Hofstra and Cline, 2000; Cooke and Simmons, 2000) or (b) metamorphic sources with values ranging from -2 to >+10‰ (Groves et al., 1998). The light $\delta^{34}S$ compositions occurring at the Padan porphyry Cu-Mo Prospect ranging from -13 to -8‰ may be explained by formation during oxidising conditions, as described by Heithersay and Walsh (1995). Post-main gold ore SMD Stage 5 stibnite also has $\delta^{34}S$ values similar to those in magmatic systems (Table 8.4).

3) Main gold ore pyrite: The light $\delta^{34}S$ values found in SMD Stage 4A pyrite (Pyrite 4A) ranging from -28.8 to -2.5‰ are similar to values reported for (a) late gold ore stage pyrite at the Meikle Carlin-type deposit, Nevada, ranging from -32.1 to -1.9‰ (Emsbo et al., 2003), and (b) the Permian sedimentary rock-hosted main gold ore stage pyrite in the Dian-Qian-Gui Carlin-type gold deposits, ranging from -30 to >+15‰ (Zhang et al., 2005; Table 8.4). Processes of thermal sulphate reduction described by Aerhart (1996) and Gammons (1997) involving $H_2S$ sourced from hydrocarbons and/or bacterial sulphate reduction (Emsbo et al., 2003) are possible mechanisms to enable the formation of the light $\delta^{34}S$ values associated with the SMD main gold ore stage Pyrite 4A.

Overall, main primary copper ore stage Chalcopyrite 3C (SMD Stage 3C) has $\delta^{34}S$ values centred at 0±2 ‰ indicating a likely magmatic source for sulphur. In contrast, the characteristic light $\delta^{34}S$ values obtained for main gold ore stage Pyrite 4A (SMD Stage 4A) have sulphur isotopic signatures more characteristic of derivation from sedimentary origins.
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8.4.4 Lead isotopes

The preliminary regional SE Asia Pb isotope studies initiated by CODES report that the SE Asia growth curve is very similar to the Stacey and Kramer (1975) Pb growth curve (Khin Zaw et al., 2007; Khin Zaw and Meffre, 2007). The lead isotope data generated in this study all plotted above the Stacey and Kramer (1975) terrestrial evolution growth curve, implying a crustal Pb source for the galena and pyrite samples analysed from the SMD (Chapter 7, Section 7.4). Furthermore, at least two characteristic populations of Pb isotope data were identified for pre-main gold ore stage mineralisation, comprising (a) a less radiogenic Pb associated with SMD Stage 3A galena associated with a paragenetically early carbonate-hosted style of base metal mineralisation mainly hosted by Devonian aged bioclastic dolomite, and (b) a paragenetically later but also more radiogenic Pb occurring in SMD Stage 3B galena and SMD RDP samples that are hosted by younger Early Permian RDP intrusions. These results imply that there are at least two potential sources of Pb identified in the SMD pre-main gold ore stages, comprising (1) an older less radiogenic carbonate-hosted source, and (2) a younger RDP intrusion-associated source.

Distinctively, the high-grade main gold ore SMD Stage 4A pyrites (Pyrite 4A1 to 4A4) yielded a wide range of Pb isotope values, implying that these pyrites could be sourcing Pb locally from both (a) Ordovician to Devonian siliciclastic and carbonate rocks hosting SMD Stage 3A galena, and (b) from Early Permian aged RDP intrusions that host SMD Stage 3B galena (Section 7.4). The currently available Pb isotope literature does not describe the sources of Pb in the Dian-Qian-Gui Carlin-type gold deposits in China to allow comparisons with the SMD data. However, Tosdal et al. (2003) report the occurrence of two distinct isotopic sources of Pb in some of the Nevada Carlin-type gold deposits in Nevada, namely the Getchell and Turquoise Hill deposits, which are interpreted to have Pb derived from both Neoproterozoic clastic rocks and the Orдовician to Devonian siliciclastic and calcareous rocks.

Overall, this SMD Pb isotope data set is probably indicating involvement of at least two Pb isotope sources during the formation of sulphides, comprising an early less radiogenic sedimentary Pb source and a later more radiogenic RDP intrusion Pb source, as determined from the pre-main gold ore stage sulphides (i.e. SMD Stages 2, 3A and 3B). Moreover, the later main gold ore stage pyrites (i.e. SMD Stage 4A) indicate mixed Pb isotopic sources that are interpreted to be both the early less radiogenic sedimentary Pb source and the later more radiogenic RDP intrusion Pb source. Additionally, both the SMD Stage 3A galena and SMD Stage 4A pyrite Pb isotope values are similar to the Pb isotopes reported by Khin Zaw et al. (2007), Khin Zaw and Meffre (2007) and Manaka (2008) for the Early Permian Phukham intrusion related Cu-Au deposits and also the Long Chieng Track and Ban Houxai epithermal deposits in northern Laos, suggesting that the Early Permian is an important period for both copper and gold mineralisation in Laos.
8.4.5 Principal characteristics and source of the possible SMD ore fluids

Comparative bi-variate plots of the SMD Th and salinity data using the methods described by Shepherd et al. (1985) indicated at least two ore fluid processes involving (a) isothermal fluid mixing, and (b) surface fluid dilution (Chapter 7). Results suggest that the SMD Stage 3C copper ore fluids most likely formed by processes of isothermal fluid mixing involving convectively-driven hydrothermal fluid circulation that is suggested by Shepherd et al. (1985) to mainly occur around intrusive bodies. This intrusion-related geological setting is comparable to the RDP intrusions hosting the SMD Stage 3C primary copper mineralisation at the SMD copper deposits and at Padan Prospect. The presence of detectible CO₂ also suggests that the SMD Stage 3C fluids are sourced deep, and the oxygen and hydrogen isotope data indicate that they are isotopically similar to magmatic and metamorphic waters. However, the SMD Stage 3C ore fluids were more likely to be sourced from magmatic fluids considering (a) their close relationship with the SMD RDP intrusions, (b) their isothermal mixing characteristics, and (c) presence of CO₂.

Surface fluid dilution trends were identified in quartz associated with the SMD Stage 4A (main gold ore) mineral assemblages, suggesting the presence of more than one ore fluid during gold deposition. The presence of two saline fluids detected in SMD Stage 4A quartz invokes the involvement of ore fluids that are similar to (1) metamorphic and/or evolved meteoric fluids for those with low-moderate salinities ranging from 4.3 to 8.6 wt% NaCl equiv., and (b) both magmatic and/or basinal brine origins for fluids with moderate-high salinities from 12.1 to 13.7 wt% NaCl equiv. (Chapter 7). However, the SMD Stage 4A ore fluid Th values are hotter than those in the classical Nevada Carlin-type gold deposits but are more similar to those occurring in amagmatic (metamorphic) systems associated with Phanerozoic orogenic gold deposits or magmatic systems containing DDGD-types, and low temperature porphyry Cu-Au deposits. Furthermore, the SMD Stage 4A main gold ore fluids yielded δ¹⁸O values that also occur in the known ranges for metamorphic and magmatic waters.

In conclusion, both magma-related fluids associated with the RDP intrusions, and evolved meteoric waters in the Sepon Basin are the most likely sources of ore fluids during the SMD Stage 4A gold mineralisation, although involvement of amagmatic ore fluids and connate brines cannot be ruled out.
8.5 SHGD GENETIC MODELS

8.5.1 Introduction

Two main classes are recognised for the sedimentary rock-hosted, disseminated gold deposits in Nevada (i.e. SHGD), namely (1) Carlin-type and (2) distal-disseminated Au deposits (DDGD) as described by Hofstra and Cline (2000) and references therein; Hofstra et al. (2003), Cunningham et al. (2004), Muntean et al. (2004), Cline et al., (2005), Ressel and Henry (2006) and Johnston et al. (2008). Both these gold deposit types can occur in mineral districts containing various combinations of SEDEX, epithermal, proximal skarn, porphyry and volcanic-hosted systems containing precious and/or base metals, which has led to the development of several proposed genetic models to explain gold formation in the Nevada SHGD (Hofstra and Cline, 2000; Hofstra et al., 2003; Muntean et al., 2004; Cline et al., 2005; Emsbo et al., 2006). Recent discussions propose a continuum between both the Carlin-type and DDGD-types, but acknowledge that further studies are required to test this hypothesis (Johnston and Ressel, 2004; Ressel and Henry, 2006).

The classical Carlin-type gold deposits exhibit several physical and geochemical similarities with the DDGD-types, principally both containing disseminated gold (Hofstra and Cline 2000; Muntean et al., 2004; Cline et al., 2005). However, differences exist between them with respect to the DDGD-types (a) being predominantly intrusion-related, (b) commonly having spatial and temporal associations with skarn and/or porphyry deposits, (c) commonly having higher Ag and base metal contents, (d) having gold ore fluids with generally higher deposition temperatures and salinities, and (e) with ore fluid isotopic data supporting magmatic origins (Sillitoe and Bonham, 1990; Cunningham et al., 2004; Cline et al., 2005; Ressel and Henry, 2006; Johnston et al., 2008). Furthermore, Carlin-type gold deposits are (a) not usually spatially associated with coeval intrusions, (b) generally formed at lower temperatures (i.e. <240°C), and (c) having isotopic ore fluid isotopic and geochemical compositions indicating contributions from sedimentary sources and evolved meteoric fluids in addition to magmatic and metamorphic contributions (Hofstra and Cline, 2000; Seedorff and Barton, 2004; Cline et al., 2005).

At least four main ore-fluid models are currently used to explain gold ore formation in the Carlin-type and/or the DDGD-type deposits, namely (1) meteoric (water circulation) also known as surface derived and/or basinal-type (Ilchik and Barton, 1997; Emsbo et al., 2003), (2) metamorphic (orogenic) also called amagmatic-type (Hofstra and Cline 2000 and references therein, Kerrich et al., 2000; Seedorff and Barton, 2004 and Cline et al., 2005), (3) magmatic also referred to as epizonal pluton-type (Sillitoe and Bonham, 1990; Johnston and Ressel, 2004; Ressel and Henry, 2006; Johnston et al., 2008) and (4) fluid mixing involving combinations of model types (1), (2) and (3), as described by Berger and Bagby (1991), Kuhlen and Rose (1995), Hofstra and Cline (2000) and Cline et al. (2005).
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The current Carlin-type gold deposit genetic models (1), (2) and (3) are collectively represented in Fig. 8.2, and model (4) is shown in Fig. 8.3. The merits and problems associated with these four main genetic models are discussed in turn to assess their relevance to gold deposit formation in the SMD, and a genetic model for hypogene mineralisation in the SMD SHGD and SMD copper deposits will be proposed in Section 8.6.

8.5.2 Meteoric water model

The meteoric water model pertains to the leaching of metals from rocks by deeply-circulating evolved meteoric water during regional extension, and deposition in shallow environments involving lateral flow in the near surface environment (Fig. 8.2; Dickson et al., 1975; Radtke et al., 1980; Ilchik and Barton, 1997; Emsbo et al., 2003; Seedorff and Barton, 2004; Cline et al., 2005). The early forms of this model invoked similar conditions to those in low-sulphidation epithermal systems (Dickson et al., 1975; Radtke et al., 1980). The current meteoric model is explained by Seedorff and Barton (2004) as comprising (a) a network of fluid conduits involving faults, fractures and pores that are required to enable the flow of meteoric fluids to scavenge metals, (b) early stage meteoric fluid flow up and along thermal gradients that can be enhanced by topography, burial and/or spatially associated magmatism, and (c) continuation of fluid migration to lower pressure areas, mainly along structures and permeable strata to interact with other rocks and fluids, to cool and then potentially deposit metals, dependent upon a variety of chemical and physical conditions present at the trap site.

Hence, the Eocene period of extension in Nevada is interpreted to provide favourable conditions for this model due to development of a regional extensional fault system and crustal heat sources generated by both topographic differences and spatially associated intrusions enhancing the flow of surface-derived fluids to leach and transport metals (Seedorff and Barton, 2004).

Problems involved with application of the meteoric water model to the both the Carlin-types and the DDGD-types include: (a) Carlin-type gold deposits generally contain higher gold endowments than low-sulphidation epithermal deposits (Hofstra and Cline, 2000; Cooke and Simmons, 2000), (b) the gold deposits that occur outside of the favourable structural domains that were highly extended at the surface to enable surface fluid flow regimes are not explained by this model (Seedorff and Barton, 2004), (c) the presence of deeply sourced metamorphic and/or magmatic ore-fluids in some of the gold deposits is not accounted for in this model (Cline et al., 2005), (d) fluid inclusion evidence for boiling is also lacking in the Carlin-type gold deposits (Sillitoe and Bonham, 1990; Berger and Bagby, 1991), (e) the ore fluids are generally more saline with >5 wt % NaCl equiv., and (f) CO₂ occurs in some of the DDGD-type and Carlin-type gold deposits, indicating formation depths of >2 km which are deeper than is normal for epithermal systems (Kuehn and Rose, 1995; Arehart, 1996, Hofstra and Cline, 2000).
The involvement of meteoric waters in the SMD mineralising systems cannot be ruled out due to indications of surface dilution trends from the SMD fluid inclusion data confirming the presence of at least two fluids during SMD Stage 4A (Chapter 7). Both low and high salinity fluid inclusions in quartz from main gold ore SMD Stage 4A imply the involvement of ore fluids that are similar to evolved meteoric fluids for those with low-moderate salinities <9 wt % NaCl equiv., but also involving the presence of magmatic or connate brines for the fluids comprising moderate-high salinities >9 wt% NaCl equiv. (Section 8.4.5). Therefore, application of the meteoric water model cannot solely explain the formation of both gold and copper mineralisation in the SMD, due to (a) indications of magmatic and/or metamorphic fluids from the oxygen and hydrogen isotope data and also the presence of CO₂ in fluid inclusions during the formation of SMD Stage 3C main primary copper ore mineralisation (i.e. Chalcopyrite 3C), and (b) the SMD Stage 4A main gold ore fluids in quartz yielded oxygen isotope values that also occur in the ranges for both metamorphic and magmatic waters.

Fig. 8.2. Carlin-type gold deposit ore-fluid models (1), (2) and (3) (modified after Seedorff and Barton, 2004).

(A). Model 1 shows normal faults acting as recharge conduits with surface-derived waters descending down to the brittle-ductile zone and then forming gold deposits as the ore-fluid return towards the surface. Model 2 Magmatic inputs (3) combined with metamorphic waters (2) at the brittle-ductile transition zone then ascend to towards the surface along faults. (B). Model 3 shows the involvement of multiple intrusions with the development of ore fluids in a magmatic hydrothermal system. Inputs of unevolved meteoric waters are shown in all models (1a).
8.5.3 Metamorphic (orogenic) ore-fluid model

The metamorphic ore fluid model involves generation of fluids from deep crustal and mantle sources by prograde metamorphic devolatilisation during periods of tectonism, accompanied by focussed discharge of these fluids along regional faults to epizonal depths (Fig. 8.2; Groves et al., 1998; Seedorff and Barton, 2004; Cline et al., 2005). Furthermore, the metamorphic fluids associated with gold deposition in this model commonly contain CO₂ and CH₄, supporting derivation from deep sources (Mernagh et al., 2007). Pre-existing reservoirs of metamorphic fluids tapped during periods of extension are also suggested as alternative sources by Seedorff and Barton (2004) and references therein, but this hypothesis is difficult to demonstrate (Cline et al., 2005). Studies of the Getchell Carlin-type deposit in Nevada have yielded isotopic data supporting deeply-sourced metamorphic or magmatic ore fluids (Cline et al., 1997; Cline et al., 2005). Radiogenic data also support the presence of deeply sourced ore-fluids at some of the Nevada Carlin-type gold deposits (Tosdal et al., 2003; Cline et al., 2005). However, current concerns about the application of this model for the Nevada Carlin-type gold deposits include: (1) difficulties with confirming the effects of Eocene metamorphism, (2) a paucity of coeval intrusive centres in some districts, and (3) some deposits only produce stable isotope data supporting sedimentary and meteoric origins for ore fluids and lack evidence for metamorphic ore fluids (Hofstra and Cline, 2000; Cline et al., 2005). Furthermore, the metamorphic model does not account for stable isotope data supporting magmatic signatures at some of the Nevada DDGD-types, in particular for sulphur, oxygen and hydrogen at the Cove deposit (Johnston et al., 2008).

The involvement of metamorphic fluids during formation of both the SMD copper and gold deposits is possible, based on: (a) the presence of coeval Early Permian RDP intrusions during the formation of the SMD Stage 3C primary copper mineralisation (i.e. Chalcopyrite 3C), (b) indications of metamorphic contributions to the ore fluids detected in the oxygen and hydrogen isotope data from quartz associated with Chalcopyrite 3C, (c) the detection of CO₂ in SMD Stage 3C quartz, and (d) oxygen isotope data indicating contributions of metamorphic and/or magmatic fluids in SMD stage 4A quartz associated with main gold ore Pyrite 4A (Table 8.4). However, application of the metamorphic model solely to explain the formation of both copper and gold in the SMD is not reasonable due to: (a) indications of other fluids such as evolved meteoric fluids during the formation the SMD Stage 4A gold ore-fluids, based on fluid inclusion surface dilution trends and the presence of at least two contrasting ore fluids, one being low salinity and the other moderately saline, (b) the presence of magmatic sulphur isotopic signatures detected for Chalcopyrite 3C, and (c) indications of possible magmatic ore-fluid contributions based on higher salinity ore fluids and oxygen isotope data from both SMD Stages 3C and 4A (Chapter 7 and Table 8.4).
8.5.4 Magmatic (intrusion related) ore fluid model

The magmatic (intrusion-related) ore fluid model has mainly been used to explain deposits that contain Carlin-like gold ore features but predominantly show magmatic ore fluid and stable isotope characteristics and are also intrusion-hosted or occupy distal and/or adjacent sites near skarn and/or porphyry intrusions (Alvarez and Nobel, 1988; Sillitoe and Bonham, 1990; Hofstra and Cline, 2000; Seedorff and Barton, 2004; Cline et al., 2005). The early magmatic models by Sillitoe and Bonham (1990) described examples of Carlin-like gold deposits in distal positions near porphyry intrusions, but located beyond the associated zones of intrusion-related skarn alteration, and also proposed that gold is contributed from a deep magmatic-hydrothermal source (Fig. 8.2). The Carlin-like deposit case studies presented by Sillitoe and Bonham (1990) to support the magmatic model include (1) Melco, Barneys Canyon and Mercur in the Bingham Porphyry district, Utah, USA, (2) Lone Tree, Nevada, USA, and (3) Bau in Malaysia. These Carlin-like deposits are also referred to as DDGD-types (Hofstra and Cline, 2000; Kerrich et al., 2000; Ressel et al., 2000; Muntean et al., 2004). Other examples of DDGD-type deposits in Nevada that are also described as having physical and/or geochemical features supporting the magmatic model include: Beast (Ressel et al., 2000), Deep Star (Heitt et al., 2003) and Cove (Johnston et al., 2008).

The principal problem associated with application of the magmatic model to solely explain the formation of the Nevada Carlin-type gold deposits is the lack of evidence for trends towards higher temperature alteration zones, in particular the skarn and/or porphyry types (Hofstra and Cline, 2000; Seedorff and Barton, 2004; Cline et al., 2005). Moreover, the magmatic model also requires large volumes of gold-bearing fluids to travel great distances from the source intrusions without depositing gold until reaching the deposition site (Hofstra and Cline, 2000). Furthermore, although the Getchell Carlin-type deposit in Nevada also contains stable isotope ore-fluid components that support both deeply sourced magmatic and/or metamorphic fluids, the nearest Eocene intrusion is located several kilometres away and therefore no direct genetic link with Eocene magmatism has been established (Hofstra and Cline, 2000; Cline et al., 2005).

By comparison, the SMD gold and copper deposits have spatial association with the Early Permian RDP intrusions in geological setting, ore mineral assemblages and trace element zonation, comprising (a) distally located SHGD, (b) proximal primary copper-bearing retrograde skarns with overlying supergene and exotic copper, and (c) centrally positioned RDP porphyry intrusions containing minor sulphide Cu-Mo mineralisation (Fig. 8.1). Moreover, molybdenite associated with Chalcopyrite 3C in the retrograde assemblages cutting RDP intrusions at the Thengkham South copper deposit and Padan Cu-Mo Prospect was constrained by Re-Os dating to the 7 Ma interval between 287.2±1 Ma to 280.2±1Ma, which is coeval with RDP emplacement at both of these areas. Furthermore, geochemical evidence of magmatic
contributions during sulphide formation hosting gold and copper mineralisation in the SMD includes: (1) the presence of magmatic sulphur isotope signatures detected for pre-main gold ore SMD Stage 3B base metals in the SMD SHGD, and also for main copper ore SMD Stage 3C chalcopyrite, (2) indications of possible magmatic ore fluid contributions based on oxygen isotope data from both SMD Stage 3C (main copper ore) and SMD Stage 4A (main gold ore), (3) detection of CO₂ in SMD Stage 3C ore fluids in quartz implying deeply sourced fluids of probable magmatic and/or metamorphic origins, and (4) the presence of similar radiogenic lead values in SMD Stage 4A pyrite types that are comparable to the radiogenic values from the SMD Early Permian RDP intrusions. Although these lines of evidence supports magmatic origins, the single application of this model to describe the formation of the SMD gold and copper deposits is not plausible due to indications of other fluid contributions, possibly involving evolved meteoric and metamorphic ore fluids that were previously discussed for these models in Sections 8.2 and 8.3 respectively.

8.5.5 Evolved fluid mixing model (multiple ore fluids)

The observations of more than one ore fluid present during gold formation in the Nevada Carlin-type gold deposits has led to the development of genetic models involving fluid mixing, mainly comprising deeply sourced magmatic and/or metamorphic ore fluids mixing with upper crustal circulating meteoric waters (Berger and Bagby, 1991; Kuehn and Rose, 1995; Hofstra and Cline, 2000; Cline et al., 2005). The early Carlin-type fluid mixing models invoke Tertiary magmatic fluids mixing with circulating meteoric waters (Kuehn and Rose, 1995). An alternative ore fluid mixing model advocated the involvement of metamorphic fluids generated during extension and/or magmatism mixing with circulating meteoric fluids that ascend to shallow crustal level depositional sites (Hofstra and Cline, 2000).

Subsequent refinement of the earlier models by Cline et al. (2005) proposes mixing of magmatic, metamorphic and meteoric ore-fluid components (Fig. 8.3). Briefly, their fluid mixing model involves: (1) emplacement into the lower crust of mantle-derived magmas consisting of mantle derived volatiles and isotopically young components, which also assimilate additional volatile components and possibly Au derived from associated prograde metamorphism, (2) continued ascent of the resultant crustal melts, saturated in exsolved hydrothermal fluids and volatiles, possibly transporting bisulphide complexed Au, (3) continued upward transportation along extensional fluid pathways of over-pressurised exsolved hydrothermal fluids comprising both magmatic and metamorphic components, which become diluted when they mix with upper crustal circulating meteoric waters, developing compositionally evolved ore-fluids principally consisting of scavenged Au, As, Hg, S and Pb from the host rock packages.
The involvement of circulating meteoric waters is considered to be an important component in the overall development of Carlin-type gold deposits as they are interpreted to leach older pre-existing enrichments of metals in the rock packages they migrate through (i.e. from auriferous diagenetic pyrites and/or earlier pyrite-rich base-metal systems), generating H₂S-rich fluids, enabling the scavenging of Au and trace metals (Hofstra and Cline, 2000; Emsbo et al., 2003; Cline et al., 2005; Emsbo et al., 2006). Precipitation of metals from the Au-bearing mixture of evolved ore fluids is interpreted to occur upon fluid migration into permeable rocks, sulphidising reactive iron in the enclosing host rocks such as iron carbonates, resulting in adsorption on to pre-existing pyrite grains or co-precipitation of Au and associated bisulphide complexed metals, forming auriferous and trace element-rich pyrite (Kuehn and Rose, 1995; Hofstra and Cline, 2000; Cline et al., 2005; Emsbo et al., 2006).

Fig. 8.3. The evolved fluid mixing model developed by Cline et al. (2005) illustrating the interpreted spatial relationships between, magmatic, metamorphic and meteoric fluids during the formation of Carlin-type gold deposits. This figure also shows the interpreted crustal locations where ore-fluid components and Au are potentially contributed. Additional explanation is provided in the text.
8.6 GENETIC MODEL FOR GOLD IN THE SMD DEPOSITS

8.6.1 Overview

Insights into the source of metals occurring in the SMD have mainly been gained in this study through the identification of multiple gold depositional events in distinct paragenetic stages in both the gold and copper systems. The genetic model proposed for deposition of gold in hypogene minerals at the SMD gold and copper deposits accounts for at least three gold deposition events, commencing with: (1) early concentrations of very low grade gold (<0.3 ppm Au) in syngenetic or syndiagenetic pyrite interpreted to have formed under euxinic conditions in the SMD (i.e. SMD Stages 1 and 2), (2) deposition of low grade gold (<3 ppm Au) in the proximal Cu skarn and porphyry Cu (-Mo) deposits associated with RDP emplacement into the SMD comprising: (a) early base metal sulphides (SMD Stages 3B) and (b) later main copper ore stage Chalcopyrite 3C (SMD Stage 3C), and (3) later development of DDGD-type high grade gold (>1 to 293 ppm Au) deposited during SMD Stages 4A and 4B, after emplacement of SMD Stage 3C. Therefore, this model incorporates: (1) syngenetic and syndiagenetic processes for SMD Stages 1, 2, and 3A, (2) magmatic hydrothermal and associated metamorphic ore fluid processes for SMD Stages 3B and 3C, and (3) mixing process involving magmatic, metamorphic and meteoric fluids for SMD Stages 4A, 4B and 5. Section 8.7.2 will present this SMD genetic model in more detail, using the available geological, geochronological, mineralogical and geochemical data described in the previous Chapters. This SMD genetic model is also represented in Fig. 8.4.

8.6.2 Proposed genetic model for gold in the SMD gold and copper deposits

The proposed genetic model for gold in the SMD gold and copper deposits is described using the paragenetic sequence developed for SMD Stages 1 to 5 and also accounts for gold from sedimentary, metamorphic and magmatic sources. This genetic model will also be explained using three major paragenetic stages of gold occurrence, namely (1) pre-main gold ore stages, (2) main gold ore stages and (3) post-main ore stages.

8.6.2.1 Pre-main gold ore stages

Early development of the Sepon Basin, is interpreted to commence before or during the Ordovician during sinistral movement along the Truongson Foldbelt, generating E-W shortening and subsequent onset of N-S rifting of metamorphosed Upper Proterozoic basement rocks. This period also established the major basin forming faults, comprising steep ENE-trending normal faults and NW- and WNW-trending strike slip transfer faults (Marten, 1997, 1998a; Coller, 1999; Smith, 2003). Subsequent deposition of sediments in the SMD commenced in an interpreted north-dipping half graben, mainly comprising Ordovician to Early Silurian siliciclastic rocks consisting of sandstone, siltstone and shale and Silurian to Middle Devonian dominantly carbonate rocks composed of calcareous shale, bioclastic dolomite and
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chort (Morris, 1996, 1997, 1998, 2006; Ekins, 2005). The Middle Devonian Discovery Formation calcareous shale hosts SMD Stage 1 framboidal pyrite which is interpreted to have formed during to immediately after sedimentation. Gold occurrences associated with SMD Stage 1 framboidal pyrite are not known. The later stages of SMD Stage 1 consist of early ferroan dolomite developed along stylolites and cleavages cutting calcareous shale, and in turn cut by calcite veins.

SMD Stage 2 is interpreted to have formed after sedimentation and later in the diagenesis of the Sepon Basin. At least three types of gold-poor syn-diagenetic pyrite developed during SMD Stage 2 comprising: (a) nodular-shaped pyrite (Pyrite 2A), (b) euhedral spongy-textured pyrite (Pyrite 2B), and (c) euhedral angular pyrite (Pyrite 2C). These pyrite types are mainly observed in the Middle Devonian Discovery Formation and they only contain low levels of gold, generally <0.3 ppm in the pyrite cores and <0.1 ppm along the pyrite rims, implying the likely accumulation of syngenetic or syndiagenetic gold during pyrite formation and also potentially providing a pre-concentrated sedimentary gold source (Fig. 8.4).

Abbreviations used:
SHGD = sedimentary rock-hosted gold deposit, SKN = skarn, ST = paragenetic stage, PY = pyrite, RDP = rhyodacite porphyry intrusion, DSE = Discovery East (SHGD), KHN = Khanong copper deposit, NLU = Nalou (SHGD), TKM = Thengkham South copper deposit, TKN = Thengkham North copper deposit, VAT = Phavat (SHGD), CHE = chert, CSH = calcareous shale, DOL = bioclastic dolomite, SLT = siltstone, SST = sandstone, NMK FM = Nam Kian Formation, DIS FM = Discovery Formation, NLU FM = Nalou Formation, KGK FM = Kengkeuk Formation, VNG = Vang Ngang Formation, NPA = Nampa Formation.

Fig. 8.4. Simplified geology and genetic model showing the formation of the SMD SHGD (yellow dashed outline) and copper skarn deposits (green fill). The potential locations and processes involved with the generation of hydrothermal fluids that evolve to become ore fluids for the SMD gold and copper deposits are also shown. The discussion for this model is provided in the text (Section 8.7). Abbreviations used: SHGD = sedimentary rock-hosted gold deposit, SKN = skarn, ST = paragenetic stage, PY = pyrite, RDP = rhyodacite porphyry intrusion, DSE = Discovery East (SHGD), KHN = Khanong copper deposit, NLU = Nalou (SHGD), TKM = Thengkham South copper deposit, TKN = Thengkham North copper deposit, VAT = Phavat (SHGD), CHE = chert, CSH = calcareous shale, DOL = bioclastic dolomite, SLT = siltstone, SST = sandstone, NMK FM = Nam Kian Formation, DIS FM = Discovery Formation, NLU FM = Nalou Formation, KGK FM = Kengkeuk Formation, VNG = Vang Ngang Formation, NPA = Nampa Formation.
The associated trace elements Cr-Zn-Sb-Mn-Se-Ba-Te present in the SMD Stage 2 pyrites are also similar to those described by Large et al. (2007) that are concentrated by organic processes in reduced sedimentary environments. Moreover, SMD Stage 2B pyrites yielded a wide range of light and heavy $\delta^{34}$S values from -11.6 to +33‰ and are comparable to the known ranges of $\delta^{34}$S values for sedimentary pyrite in other SHGD described by Hofstra (1997) and Zhang et al. (2005). The detection of less radiogenic lead from a crustal source in this pyrite generation implies incorporation of Pb from older sources in the SMD. Later pink calcite (Calcite 2) fills fractures cutting SMD Stage 2 pyrite and also cuts stylolites and cleavages containing Stage 1 ferroan dolomite.

Later SMD Stage 3A base metal assemblages consisting of pyrite-sphalerite-galena-dolomite mainly formed along epigenetic veins and fractures cutting carbonate rocks, predominantly dolomitised Nalou Formation bioclastic limestone. SMD Stage 3A contains no known gold concentrations but does contain less radiogenic lead similar to that occurring in SMD Stage 2 pyrites, indicating similar lead derivation from older crustal sources. Although SMD Stage 3A pyrite, sphalerite and galena yielded a combined narrow range of $\delta^{34}$S values from -6 to +4‰ that is similar to that reported for magmatic systems, they also occupy the known ranges for Irish-type base metal deposits described by Hitzman (1998) that have $\delta^{34}$S values from -20 to +15‰. Additionally, the timing of dolomitisation of the original Middle Devonian Nalou Formation bioclastic limestone hosting SMD Stage 3A is not constrained but is considered important, as it would have produced rheological contrasts between brittle dolomitised rocks and ductile calcareous shale rocks that are interpreted by Smith et al. (2005) to enhance sites for gold ore fluid permeability subsequent to deformation events.

8.6.2.2 Main gold ore stages

The main gold ore stages commence with gold-bearing pyrite formed in association with RDP intrusions during SMD Stages 3B and 3C that contain low grades of gold (<3 ppm Au), mainly occurring as inclusions. Formation of the highest grades of gold ranging from >1 to 293 ppm Au occurs toward the end of the main gold stage during SMD Stage 4A, with gold predominantly sited in arsenic-enriched rims on earlier pyrite generations.

8.6.2.2.1 Main gold ore stage: Early low grade gold formation

Emplacement of rhyodacite porphyry (RDP) intrusions into the SMD sedimentary sequence commenced during the Early Permian between 297±7 and 280±6 Ma (this study). Prograde garnet and pyroxene skarn developed in carbonate rocks, mainly in Nalou Formation dolomite and underlying Kengkeuk Formation calcareous shale. Later stage SMD Stage 3B base metal veins also formed, comprising an early retrograde assemblage of pyrite-sphalerite-galena-quartz-dolomite at both the proximal copper skarn and distal SHGD geological settings, cutting RDP, dolomite and calcareous shale host rocks. The SMD Stage 3B sulphides mainly comprise $\delta^{34}$S values centred at 0±5‰, indicating a possible magmatic origin, but are also
associated with $\delta^{18}$O and $\delta^D$ compositions in quartz that suggest metamorphic contributions. Moreover, low grades of gold (<3 ppm Au) occur as inclusions incorporated in the SMD Stage 3B pyrite in association with elevated levels of Bi, Cu, and Se, implying contributions of these metals from magmatic sources. Furthermore, lead isotope results from SMD Stage 3B galena contain similar isotopic levels of radiogenic lead to those determined for the SMD RDP intrusions, further confirming the likely formation of the SMD Stage 3B mineral assemblages mainly from magmatic fluids and minor contributions from metamorphic fluids (Fig. 8.4).

The SMD Stage 3C late retrograde epigenetic veins associated with RDP emplacement comprise quartz-chalcopyrite+bornite+molybdenite+hematite that cut RDP, dolomite and calcareous shale rocks and also the earlier mineral stages in both the proximal Cu skarn and porphyry Cu-Mo geological settings. SMD Stage 3C is the main primary copper deposition stage that commonly comprises chalcopyrite (Chalcopyrite 3C) that also contains inclusions of low grade gold ranging from 0.06 to 0.9 ppm Au at both the proximal skarn and porphyry deposits. Chalcopyrite 3C is coeval with molybdenite that yielded Re-Os dates of $287^{+1}_{-1}$ Ma and $280^{+1}_{-1}$ Ma at the Thengkham South copper deposit and at the Padan porphyry Cu-Mo Prospect respectively, also confirming that Chalcopyrite 3C is formed syn- to early post emplacement of the Early Permian RDP intrusion at both of these locations. Other indications of Chalcopyrite 3C forming from magmatic ore fluids include (a) $\delta^{34}$S values centred at $0^{+2}_{-2}$‰ and (b) low to moderate fluid inclusion salinities ranging from 7.7 to 11.2 wt % NaCl equiv., and (c) isothermal fluid mixing characteristics. Additionally, possible minor contributions of deep source metamorphic ore fluid components during the formation of SMD stage 3C quartz are indicated by (a) $\delta^{18}$O and $\delta^D$ compositions, and (b) the presence of CO$_2$. The inclusions of gold and the presence of high trace element levels of Bi, Se, Zn and Mo also occurring in Chalcopyrite 3C indicate a strong magmatic association in the derivation of these metals, although involvement of metamorphic contributions of gold cannot be ruled out. The presence of SMD Stage 3C primary hematite suggests that the ore fluids were oxidised enabling the transport of copper at low homogenisation temperatures ranging from 175 to 260°C. Precipitation of the oxidised copper-bearing ore fluids to form Chalcopyrite 3C is potentially triggered by redox changes when they encounter chemically reactive carbonate rocks in contact with reduced carbonaceous and calcareous shale rocks (Fig. 8.4).

### 8.6.2.2.2 Main gold ore stage: Late high grade gold deposition

The SMD Stage 4A high grade main gold mineralisation is characterised by micron-sized disseminations of gold associated with quartz that fills fault zone breccias, veins and micro-fractures cutting all rock types in the SMD, including all the previous SMD Stage 1 to 3C mineral assemblages. The timing of SMD Stage 4A main gold ore stage remains poorly constrained, but is interpreted to be during a 33 to 37 Ma window of opportunity, commencing:
(a) after the youngest RDP intrusion emplacement at 280±6 Ma (Early Permian), and (b) before to during the regional 245 Ma (Early Triassic) dextral movement along the Truong Son Fold Belt reported by Leprivier et al. (1997) that is also similar in timing to the emplacement of granite adjacent to the Sepon Basin dated between 243±3 Ma and 247±4 Ma at Ban Sopmi-Kengkok (this study). Taking into consideration these events, a fluid mixing model similar to that described by Cline et al. (2005) is most applicable to explain the origins of high-grade gold during SMD Stage 4A, due to the likely presence of (1) magmatic fluids generated during (a) the Early Permian from RDP intrusions, or (b) the Early Triassic Granites at Ban Sopmi-Kengkok, (2) possible generation of associated metamorphic fluids by (a) contact metamorphism from Early Permian RDP intrusions, or (b) contact metamorphism from Early Triassic Granites at Ban Sopmi-Kengkok and (3) evolved meteoric fluids within the SMD.

Based on the constraints discussed above, the proposed scenario for the origins of SMD Stage 4A high grade gold involving a fluid mixing model is explained here. After the Early Permian RDP intrusions were emplaced into the SMD producing the main copper ore SMD Stage 3C, remnant deeply-sourced CO₂-bearing magmatic fluids most likely contained Cu, Bi and Se in addition to Au and radiogenic Pb. Metamorphic fluids generated during the intrusion of Early Permian RDP possibly contributed additional Au sourced from the surrounding sedimentary rocks. Alternatively, contributions of deep-seated CO₂-dominant metamorphic fluids could also have been generated during contact metamorphism during the emplacement of Early Triassic granites (243 to 247 Ma) at Ban Sopmi-Kengkeuk, but this hypothesis is not constrained. During hydrothermal fluid migration, processes involving magmatic heat, tectonic movement and/or compaction in the SMD forced the mixture of magmatic dominant and metamorphic ore fluids transporting bisulphide complexed gold upwards and along extensional fluid pathways, especially the reactivated high-angle ENE-trending faults; these permeable structures acted as fluid conduits from depths >2 km to shallower depths. Contemporaneously, meteoric waters circulating through the SMD sedimentary package are also considered to be important for leaching older pre-existing enrichments of gold and other metals from the rocks they migrated through, especially the auriferous SMD Stage 2 diagenetic pyrites and/or earlier carbonate-hosted SMD Stage 3A base metal sources, generating H₂S-rich fluids, enabling the scavenging of Au and other associated trace metals along the way (Fig. 8.4).

When the hydrothermal fluids comprising magmatic dominant and minor metamorphic components eventually mixed with upper crustal circulating evolved meteoric waters, they were diluted and subsequently formed compositionally evolved ore fluids principally consisting of additional contributions of scavenged Au, As, Tl, S and Pb and other trace elements provided by the meteoric fluids. This process also predominantly occurred along permeable fracture zones and faults. The occurrence of dominantly light δ³⁴S values preserved in the SMD Stage 4A pyrites ranging from -28 to -2‰ suggests sulphur contribution from a sedimentary
source, possibly involving processes of: (a) bacterial sulphate reduction (Emsbo et al., 2003) or (b) thermal sulphate reduction and/or fluid mixing, as proposed by Arehart (1996) and Gammons (1997). Additionally, the presence of both poorly radiogenic lead preserved in SMD Stage 4A pyrites that is similar in isotopic composition to that in SMD Stage 3A carbonate-hosted galena also supports some sourcing of lead from the SMD stratigraphy.

The precipitation of SMD Stage 4A gold and associated trace metals from the gold-bearing mixture of evolved ore fluids is interpreted to have occurred upon fluid migration into permeable rocks and or broken zones (Fig. 8.4). These gold ore fluids had moderate salinity (<12 wt% NaCl equiv.), minimum homogenisation temperatures ranging from 180 to 290°C, contained CO₂, and are H₂S-dominant and also slightly acidic to neutral in pH. These reactive fluids possibly enhanced permeability by decarbonising calcareous shale wall rocks, in particular the Middle Devonian Discovery Formation, and sulphidising reactive iron in the enclosing host rocks such as iron carbonates. Adsorption or co-precipitation of gold and associated bisulphide complexed metals occurred, forming auriferous and trace element-rich pyrite, according to the processes described by Kuehn and Rose (1995) and Cline et al. (2005).

The SMD Stage 4A pyrite in the skarn zones probably had larger contributions from magmatic ore fluids due to the presence of high levels of Cu, Zn, Bi and Se in the pyrites. Furthermore, evolved meteoric waters containing elevated levels of As, Sb, and Tl were possibly involved during the deposition of the SMD Stage 4A pyrites that occur in distal positions in the SHGD. Minor amounts of SMD Stage 4B Au-He-telluride in micro-fractures cutting all SMD Stages 1 to 4A formed later during the waning of the main gold ore formation stage.

8.6.2.3 Post-main gold ore stage

During the waning stages of the SMD hydrothermal system, a reduced flow of gold ore fluids and the dominance of meteoric waters possibly resulted in cooler fluids depositing post-main gold ore stage minerals represented by SMD Stage 5. At least three vein assemblages containing hypogene minerals with no known gold concentrations were formed, namely: (a) SMD Stage 5A: calcite-quartz-stibnite-dolomite, (b) SMD Stage 5B: quartz-dolomite, and (c) SMD Stage 5C: calcite-quartz-fluorite.

The processes involved in developing the oxide gold resources in the SMD post-main primary gold ore formation are not discussed in this study but are mentioned in Manini et al. (2001). Additionally, the origin of supergene and exotic copper oxide resources in the SMD is also not described in this study, but can be obtained from publications by Loader (1999) and Cannell and Smith (2008).
8.7 SUMMARY AND CONCLUSIONS

The main geological, mineralogical, geochronological, geochemical and genetic conclusions of this study of the SMD SHGD and the SMD copper deposits are summarised in the following sections.

8.7.1 Geological setting

- The SMD gold and copper deposits are hosted by Palaeozoic sediments in the Sepon Basin, located along the Truong Son Foldbelt, on the NE margins of the Indochina Terrane.
- The known SMD gold resources are mostly hosted by the Devonian Discovery Formation calcareous shale, with lesser amounts reported for the underlying Devonian Nalou Formation bioclastic dolomite, the Silurian-Devonian Kengkeuk Formation calcareous shale and the Ordovician-Silurian Nampa Formation claystone and siltstone sequence.
- The known SMD copper deposits are hosted by similar carbonate rocks to those occurring in the SMD SHGD, in particular the Devonian Nalou Formation bioclastic dolomite and the Silurian-Devonian Kengkeuk Formation calcareous shale.
- Intrusion of rhyodacite porphyry (RDP) mainly occurred along pre-existing faults during the Early Permian, constrained by U-Pb dating of zircons to between 280±6 and 297±7 Ma.
- Principal structural trends controlling and hosting gold mineralisation in the SMD gold deposits comprise WNW-striking normal faults with steep dips, and steep ENE-striking faults with both normal and reverse movements. Gold ore zone geometries observed to date in the SMD include (1) ribbon-like bodies that are strike continuous, (2) moderate to shallow dipping sheets, not always connected to faults, and (3) fault-controlled steep sheet-like bodies (Smith et al., 2005).
- Hypogene gold and copper ore types in the SMD SHGD are epigenetic and commonly occur along steep faults and/or veins cutting all the Ordovician to Middle Devonian carbonate and siliciclastic rocks and Early Permian RDP dykes and sills.

8.7.2 Mineralogy

- Common major sulphide minerals in the SMD deposits include, pyrite, arsenic-rich pyrite, chalcopyrite, and minor sphalerite, galena, bornite and stibnite, but no realgar, orpiment or cinnabar have been observed.
- Alteration types occurring in the SMD gold deposits include (a) variable decarbonatisation of carbonate units, (b) silicification (jasperoid formation) along permeable horizons and faults, (c) locally developed argillisation along RDP contacts, and (d) variable dolomitsation of carbonate units.
Primary sulphide zones hosting copper mineralisation in skarns proximal to RDP intrusions are associated with sericite alteration along intrusion margins, in addition to (a) early prograde garnet and pyroxene skarn alteration cut by later retrograde chlorite-epidote alteration of carbonate host units, and (b) hornfels in non-calcareous sedimentary rocks.

At least 5 main paragenetic mineral assemblage stages were observed across the SMD; they are collectively grouped together as SMD Stages 1 to 5 based on the gold stage paragenetic observations from this study of (1) the adjacent to distal type SHGD, (2) the proximal Cu (-Au) skarn deposits underlying supergene copper, and (3) the porphyry Cu (-Mo) deposits. The pre-main gold ore stages include SMD Stages 1, 2 and 3A. Main gold ore comprises SMD Stages 3B, 3C, 4A and 4B, and SMD Stage 5 is post-main gold deposition.

The SMD Stage 1 assemblage is interpreted to form early in the diagenesis of the Sepon Basin (i.e. syn- to post-sedimentation), it does not contain any known gold and mainly comprises rare disseminations of framboidal pyrite (Pyrite 1) hosted by CSH rocks, with minor ferroan dolomite occurring along cleavage and stylolites in CSH rocks, which are in turn cut by small late stage milky white calcite veins.

The SMD Stage 2 consists of three types of gold-poor diagenetic pyrite, comprising: (a) semi-massive nodular-shaped pyrite (Pyrite 2A); (b) euhedral spongy-textured pyrite (Pyrite 2B), and (c) euhedral angular pyrite (Pyrite 2C). These pyrite types contain very low levels of gold, generally <0.3 ppm Au in the cores and <0.1 ppm in the rims. Characteristic pink calcite (Calcite 2) filled fractures cutting SMD Stage 2 pyrite and also cuts both cleavages and stylolites containing Stage 1 ferroan dolomite. The SMD Stage 2 is interpreted to form post-sedimentation and late in the diagenesis of the Sepon Basin.

The SMD Stage 3 represents the combined main base metal dominant group of assemblages in the SMD and consists of three sub-stages, namely: (a) the SMD Stage 3A: early carbonate-hosted pyrite-galena sphalerite-dolomite veins (i.e. in the SMD SHGD), followed by (b) the SMD Stage 3B: low grade gold-bearing RDP intrusion-hosted early retrograde veins with pyrite-sphalerite-galena-quartz-dolomite (SMD SHGD and Cu skarn deposits), and (c) the SMD Stage 3C: late low grade gold-bearing RDP intrusion-hosted retrograde veins with quartz-chalcopyrite+bornite+molybdenite (SMD Cu skarn and porphyry Cu-Mo deposits). The SMD Stage 3B mineral assemblage contains low grades of gold ranging from 0.13 to <3 ppm Au that mainly occur in veins containing pyrite and sphalerite, which were observed in all three deposit type settings, namely: (a) central porphyry (in Pyrite 3B), (b) proximal skarn (in Pyrite SKN1 and sphalerite), and (c) distal SHGD (in Pyrite 3B1 and sphalerite). SMD Stage 3C typically contains chalcopyrite with inclusions of low grade gold ranging from 0.06 to 0.9 ppm Au in the central porphyry and proximal skarn settings.
The SMD Stage 4 is the main high grade gold phase in the SMD. At least two sub-stages have been observed, namely: (a) the SMD Stage 4A pyrite comprising high grades of gold concentrated along (i) the growth rims of pyrite cores that also occur along fractures cutting SMD Stage 3 sulphides in the SMD SHGD, or (ii) associated with rough-textured pyrite cutting SKN Stage 3C assemblages in the SMD copper deposits, and (b) the SMD Stage 4B Hg-Au telluride filling fractures in the SMD Stage 3 and SMD Stage 4A sulphides. Both the SMD Stage 4A pyrite types observed in the SMD SHGD and the SMD proximal copper skarn deposits contained gold values ranging from >1 and up to 293 ppm Au.

The post-main high grade gold stage assemblages are grouped into SMD Stage 5 and comprises at least three vein assemblages, namely: (a) the SMD Stage 5A: quartz-stibnite-dolomite, (b) the SMD Stage 5B: quartz-dolomite, and (c) the SMD Stage 5C: calcite-quartz-fluorite calcite-quartz. No gold grades were observed in the SMD Stage 5 sulphides.

8.7.3 Gold occurrence

Indications of multiple gold-mineralising events in the SMD were mainly observed through the SMD Stages 2, 3B, 3C, 4A and 4B.

SMD SHGD: primary gold is not visible, is associated with pyrite and occurs in:
1. SMD Stage 2B Pyrite 2B (diagenetic), which contains <0.5 ppm Au in pyrite cores
2. SMD Stage 3B Pyrite 3B (in base metal veins), which contains <0.3 to 3 ppm Au as inclusions
3. SMD Stage 4A Pyrite 4A, which contains >3 to 200 ppm Au as overgrowths on As-rich rims
4. SMD Stage 4B sulphosalts (in veins), which contain Hg-Au-telluride

The later high grades of gold in Pyrite 4A could have been derived from the early SMD Stage 2 diagenetic pyrites in the SMD and/or from the later SMD Stages 3B and 3C pyrite types during syn- to post-emplacement of the SMD RDP intrusions.

SMD copper deposits: primary gold is not visible it is associated with pyrite and occurs in:
1. SMD Stage 3B Pyrite SKN1 (in retrograde veins), which contains <0.7 ppm Au as inclusions
2. SMD Stage 3C Chalcopyrite 3C (in retrograde veins), which contains <0.9 ppm Au as inclusions
3. SMD Stage 4A Pyrite SKN2 (fractures), which contains >1 to 293 ppm Au in As-rich pyrite

Gold deposited in the SMD Stage 3B and 3C pyrites syn- to post-emplacement of the SMD RDP intrusions potentially provides a gold source for high grade Pyrite SKN1

8.7.4 Timing of SMD mineralisation

SMD Stage 3B base metal veins occurring in the SMD SHGD and SMD copper deposits are both pre-main copper stage (SMD Stage 3C) and pre-main gold stage (SMD Stage 4A).

SMD Stage 3C molybdenite coeval with Chalcopyrite 3C was constrained by Re-Os dating to between 287±1 and 280±1 Ma at the Thengkham South deposit and at Padan Prospect.

SMD Stage 4A main gold ore Pyrites 4A and Pyrite SKN1 are younger than SMD Stage 3C.
8.7.5 Geochemistry

8.7.5.1 SMD SHGD

Characteristic trace element associations (confirmed by LA-ICPMS and PIXE NMP studies):

- SMD Stage 2B Pyrite 2B (pre-main gold ore): Pb-Ni-Co-As-Ti
- SMD Stage 3A Pyrite 3A (pre-main gold ore): As-Cu-Ni-Pb
- SMD Stage 4A Pyrite SKN 2 (main gold ore): Au-As-Sb-Pb-Cu-Ni-Ti-Zn-Mn-Ag-Tl

Sulphur isotope characteristics of gold ore sulphides:

- SMD Stage 3B (pre-main gold ore) pyrite, galena and sphalerite have $\delta^{34}$S values centred at $0 \pm 5\%$ and are similar to those in magmatic systems.
- SMD Stage 4A pyrite (main gold ore) has light $\delta^{34}$S values ranging from: -28 to -2% and are more similar to those derived from sedimentary rocks.

Ore fluid characteristics:

- The main gold ore SMD Stage 4A quartz yielded homogenisation temperature (Th) values ranging from 180 to 290°C; these results are similar to Th values in DDGD-types, but are hotter than those in typical Nevada Carlin-type gold deposits.
- The main gold ore SMD Stage 4A quartz yielded salinity values ranging from 4.3 to 8.6 wt % NaCl equiv. and 12.1 to 13.7 wt % NaCl equiv., indicating the presence of two fluids.
- Surface fluid dilution trends confirmed the presence of at least two saline fluids present in fluid inclusions from the SMD Stage 4A quartz associated with main gold stage Pyrite 4A, indicating the involvement of ore fluids that are similar to (1) evolved meteoric fluids for those with low-moderate salinities <9 wt % NaCl equiv., and (2) magmatic fluids comprising moderate-high salinities >9 wt % NaCl equiv., although involvement of amagmatic (i.e. metamorphic) fluids and/or connate brines cannot be ruled out.
- SMD Stage 4A main-gold ore fluids in quartz yielded calculated $\delta^{18}$O values ranging from 9.3 to 13.8%, which are in the range for metamorphic and magmatic waters.

8.7.5.2 SMD Copper Deposits

Characteristic trace element associations (confirmed by LA-ICPMS and PIXE NMP studies):

- SMD Stage 3B Pyrite SKN1 (pre-main gold ore): Cu-Zn-Co-Se-Ni-Bi-Mn-Te±Au
- SMD Stage 3C Chalcopyrite 3C (pre-main gold ore): Cu-Zn-Se-Bi±Au
- SMD Stage 4A Pyrite SKN2 (main gold ore): Au-Cu-As-Bi-Co-Se-Pb-Zn-Ag
- The presence of Cu-Zn-Se-Bi in primary copper ore stage Chalcopyrite 3C (SMD Stage 3C) probably implies derivation from magmatic sources during RDP intrusion emplacement.
Sulphur isotope characteristics of copper and gold-ore sulphides:

- SMD Stage 3B (pre-main gold ore) pyrite and sphalerite in retrograde skarn veins contain $\delta^{34}$S values centred at 0±2‰ and are similar to those in magmatic systems.
- SMD Stage 3C (pre-main gold ore) chalcopyrite in late retrograde skarn veins contain $\delta^{34}$S values centred at 0±2‰ and are also similar to those in magmatic systems.
- SMD Stage 4A Pyrite SKN2 (main gold ore): no $\delta^{34}$S values could be obtained.

Ore-fluid characteristics:

- Main primary copper ore stage quartz (SMD Stage 3C) yielded minimum homogenisation temperatures ranging from 175 to 260°C. The presence of primary hematite with this mineral assemblage suggests oxidising fluid conditions during mineralisation, thereby enabling copper to be transported at these low to moderate temperatures.
- Main primary copper ore (SMD Stage 3C) quartz yielded moderate salinity values ranging from 7.7 to 11.2 wt % NaCl equiv., similar to the salinities in SMD Stage 4A quartz.
- Bi-variate plots of the SMD $\delta^{18}$O and $\delta$D compositions from the SMD Stages 3B and 3C pre-main gold ore assemblages have ore fluid characteristics similar to metamorphic and magmatic waters.
- The SMD Stage 3C ore fluids in quartz associated with Chalcopyrite 3C are probably derived from magmatic sources considering (a) their close relationship with the SMD RDP intrusions, (b) their isothermal mixing characteristics, and (c) the presence of CO₂.

8.7.6 Lead isotope characteristics

- All of the RDP, galena and pyrite Pb isotope results from the SMD imply a crustal Pb source, as they plot above the Stacey and Kramer (1975) growth curve.
- Pre-main gold ore-stage mineralisation shows evidence for at least two distinct Pb isotope sources, comprising (a) less radiogenic Pb in SMD Stage 3A galena associated with a paragenetically early carbonate-hosted style of base metal mineralisation mainly hosted by Devonian bioclastic dolomite, and (b) paragenetically later but also more radiogenic Pb occurring in SMD Stage 3B galena and SMD RDP samples that are hosted by younger Early Permian RDP intrusions.
- Main gold ore-stage Pyrites 4A (SMD Stage 4A) contain a wide range of Pb isotopic sources that are interpreted to be derived from both (a) early less radiogenic sedimentary Pb sources and (b) later more radiogenic Pb from RDP intrusions.

8.7.7 Genetic model

- Geochemical data from the SMD gold and copper deposits indicate fluid mixing processes, involving (1) early magmatic and minor associated metamorphic fluids forming the SMD copper skarn and porphyry deposits (SMD Stage 3C), and (2) later interaction of the early deep magmatic and minor associated metamorphic fluids with circulating evolved meteoric fluids, possibly also sourcing S, Pb, Au and associated trace elements from sedimentary rocks for the gold deposits (SMD Stage 4A).
IMPLICATIONS FOR EXPLORATION

The primary geological and surface geochemical characteristics that are considered important during exploration for gold and copper resources in the SMD have been previously described by Loader (1999), Manini et al. (2001), Manini and Albert (2003), Smith et al. (2005), Olberg et al. (2006) and Cannell and Smith (2008), from which the main points are summarised in Chapter 1. In addition, the main points that arise from this study that may assist exploration to discover additional SMD type gold and copper resources are:

- LA-ICPMS U-Pb dating of zircons has established that the main period of RDP intrusion emplacement in the SMD is during the Early Permian between 297±7 and 280±6 Ma. The Re-Os dating of SMD Stage 3 molybdenite associated with chalcopyrite also confirmed that the main period of primary copper formation in the SMD is coeval with RDP emplacement but further constrained to between 287±1 Ma and 280±1 Ma. Stream sampling of zircons for U-Pb age dating may help to define drainages that contain populations of Early Permian zircons to assist exploration efforts to locate near surface RDP intrusions that may potentially be associated with skarn and/or porphyry-related copper and molybdenum resources but masked by the present soil profile, especially in the SMD areas to the east of the Padan Cu-Mo Prospect covered by extensive Ordovician-Silurian aged siliciclastic rock types.

- Trace element investigations involving LA-ICPMS analyses of pyrite and/or chalcopyrite could help to define areas and/or zones that may contain the following characteristic trace element associations as potential pathfinders towards gold or copper mineralisation:
  
  o SHGD (main-gold ore stage, SMD Stage 4A):
    - Au-As-Ag-Cu-Ni-Mn-Pb-Sb-Tl-Zn (First order),
    - Ba-Bi-Co-Cr-Se-Te (Second order),
    - Mo-V-W (Third order)
  
  o Retrograde copper skarns (main-copper stage, SMD Stage 3C):
    - Cu-Bi-Se-Zn (First order),
    - Ag-As-Mo-Pb-Sn-Te-Ti-V (Second order),
    - Au-Ba-Co-Ni-Sb-Tl-W (Third order)

- Trace element investigations involving LA-ICPMS to detect low levels of gold in samples containing syn-sedimentary and/or sys-diagenetic pyrites that exhibit higher gold levels in the pyrite cores than the rims may help identify areas that contain pre-main gold ore stage concentrations of gold that could provide a source for later high grade gold events.
Conventional sulphur isotope analyses of pyrite could highlight other districts and/or prospects that (a) contain base metal skarn and/or porphyry copper deposits that mostly have magmatic $\delta^{34}$S values centred at $0\pm5$‰, or (b) those that contain syn-sedimentary or syn-diagenetic pyrites with potential pre-concentrations of low-grade gold comprising wide ranging $\delta^{34}$S values from $<-11$ to $>+33$‰. Other micro-analytical sulphur isotope methods such as those involving laser ablation would be required to test small pyrites (i.e. $>200\ \mu$m) from areas of interest to determine if they are main gold stage types (i.e. SMD Stage 4A) that commonly yield light $\delta^{34}$S values ranging from: $<-28$ to $-2$‰.

Conventional lead isotope analyses of soils and/or surface rocks could be used to determine districts and/or prospects that contain carbonate-hosted base metals similar to those described for SMD Stage 3A if they contain galena with lead isotope values ranging from 18.19 to 18.29 ($^{206}$Pb/$^{204}$Pb), 15.63 to 15.70 ($^{207}$Pb/$^{204}$Pb) and 38.30 to 38.68 ($^{208}$Pb/$^{204}$Pb). Comparatively, RDP intrusions that are closely associated with primary copper mineralisation (i.e. SMD Stage 3C) generally have more radiogenic Pb isotope values ranging from 18.452 to 18.454 ($^{206}$Pb/$^{204}$Pb), 15.76 to 15.77 ($^{207}$Pb/$^{204}$Pb) and 38.86 to 38.89 ($^{208}$Pb/$^{204}$Pb), which are also similar to those for galena from SMD Stage 3B distal base metal veins in the SMD SHGD.

Some of the key ingredients that are most likely to be involved with the generation of late stage high grade SHGD resources in the SMD include: (1) pre-concentrations of low grade gold in (a) syn-diagenetic pyrite, and/or (b) pre-existing hydrothermally formed sulphide deposits, in particular RDP intrusion-related retrograde base metal skarns or copper-gold porphyries, (2) presence of iron-rich rocks in the basin that enhance sulphidation reactions like ferroan carbonates, (3) the presence of pre-existing sulphides that can provide nuclei for late-stage ore deposition, (4) magmatic and/or burial compaction processes to provide heat to drive hydrothermal fluid transport in the sedimentary basin, (5) periods of tectonism to create fluid pathways along zones of extension for evolved hydrothermal fluids to reach suitable metal trap sites, and (6) suitable reactive rocks to provide opportunities for ore fluid redox conditions to be changed to enhance metal deposition, in particular when they encounter chemically reactive carbonate rocks (dolomite) in close contact with reduced carbon-rich argillite (calcareous shale).
8.9 FUTURE RESEARCH RECOMMENDATIONS

A baseline for subsequent research into the genesis of deposits in the SMD has been established with this study of primary gold mineralisation in the gold and copper deposits. Future research that would help to constrain some of the additional questions about the SMD deposits includes:

- Conduct further systematic and detailed studies of the district-scale and deposit-scale structure in the SMD to provide additional data to be incorporated into a three-dimensional geological model to (a) understand the nature and evolution of the structural regimes that controlled the emplacement of RDP intrusions and the subsequent associated mineralisation stages, (b) delineate further likely fluid pathways to target Au and Cu mineralised zones, and (c) determine the post-mineralisation structural history of the district to gain insights into the uplift history involved with the development of the SMD supergene gold and copper deposits that provide significant economic resources.

- Where and when available from fresh drill cores, continue with studies of early stage syn-sedimentary pyrite, syn-diagenetic pyrite and framboidal pyrite, noting the thickness of the formations they occur in and their abundance to deduce if significant pre-concentrations of low grade gold could or have been sourced from them, contributing additional gold for the SMD later stage high grade gold events (i.e. SMD Stage 4A).

- When intersected in drill cores and/or during mining operations, date any younger intrusions that clearly cut gold mineralised zones to try and constrain the maximum age limits for high grade gold mineralisation in the SMD. This may also help to focus exploration to particular rock package ages if targeting gold in Laos.

- Investigate opportunities to do Re-Os dating of SMD Stage 4A high grade gold-bearing pyrite to constrain the age(s) of gold mineralisation. This could aid gold exploration in other districts where similar aged mineralisation occurs, e.g. in Laos.

- Continue building on the lead isotope database to further constrain: (a) a Pb growth curve model for the SMD, (b) the Pb isotope signatures for SMD Stage 4A high grade gold and SMD Stage 3B base metal phases, and (c) the Pb sources for gold mineralisation.