Understanding gold-(silver)-telluride-(selenide) mineral deposits

Nigel J. Cook  
*University of Adelaide*

Cristiana L. Ciobanu  
*University of Adelaide*

Paul G. Spry  
*Iowa State University*, pgspry@iastate.edu

Panagiotis Voudouris  
*University of Athens*

participants of IGCP-486

Follow this and additional works at: [https://lib.dr.iastate.edu/ge_at_pubs](https://lib.dr.iastate.edu/ge_at_pubs)

Part of the Geochimistry Commons, Geology Commons, and the Mineral Physics Commons

The complete bibliographic information for this item can be found at [https://lib.dr.iastate.edu/ge_at_pubs/354](https://lib.dr.iastate.edu/ge_at_pubs/354). For information on how to cite this item, please visit [http://lib.dr.iastate.edu/howtocite.html](http://lib.dr.iastate.edu/howtocite.html).

This Article is brought to you for free and open access by the Geological and Atmospheric Sciences at Iowa State University Digital Repository. It has been accepted for inclusion in Geological and Atmospheric Sciences Publications by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.
Understanding gold-(silver)-telluride-(selenide) mineral deposits

Abstract
Gold-(silver)-telluride (selenide) ores occur as epithermal orogenic and intrusion related deposits. Although Te and Se are chalcophile elements and share geochemical affinity with Au, formation of selenides and other elements Ag-Au require acidic or reducing environments. The thermodynamic stability conditions for Au and Agtellurides and native tellurium indicate an epithermal environment. Analysis of mineral paragenensis, textures and compositional variation in tellurides/selenides suggest petrogenetic processes involving interaction with fluids leading to Au scavenging and entrapment in tellurides, changes in chemistry/rates of fluid infiltration and attaining equilibrium in a given assemblage.

Disciplines
Geochemistry | Geology | Mineral Physics

Comments
This article is published as Cook, Nigel J., Cristiana L. Ciobanu, Paul G. Spry, and Panagiotis Voudouris. "Understanding gold-(silver)-telluride-(selenide) mineral deposits." Episodes Journal of International Geoscience 32, no. 4 (2009): 249-263. doi:10.18814/epiiugs/2009/v32i4/002.

Creative Commons License
This work is licensed under a Creative Commons Attribution-Noncommercial 4.0 License

This article is available at Iowa State University Digital Repository: https://lib.dr.iastate.edu/ge_at_pubs/354
Understanding gold-(silver)-telluride-(selenide) mineral deposits

Gold-(silver)-telluride-(selenide) ores occur as epithermal orogenic and intrusion related deposits. Although Te and Se are chalcophile elements and share geochemical affinity with Au, formation of selenides and other elements Ag-Au require acidic or reducing environments. The thermodynamic stability conditions for Au and Ag-tellurides and native tellurium indicate an epithermal environment. Analysis of mineral paragenesis, textures and compositional variation in tellurides/selenides suggest petrogenetic processes involving interaction with fluids leading to Au scavenging and entrapment in tellurides, changes in chemistry/rates of fluid infiltration and attaining equilibrium in a given assemblage.

Introduction

Gold-(silver)-telluride-(selenide) deposits are not described as a discrete class of ore deposit. Many fall, instead, into the more familiar classes of epithermal, orogenic and intrusion-related deposits, with their distinctive character linked to telluride-, and more rarely, selenide-rich mineralogy, rather than any shared genesis. The interplay between mineralogy and ore genesis provided motivation for International Geoscience Programme (IGCP) project 486 (2003-2008). IGCP-486 allowed researchers from more than 30 countries the opportunity to share scientific results at scales ranging from micro-scale study of mineral assemblages to that of gold deposit distribution within an orogenic collage.

The synthetic analogues of Bi-tellurides have structures that are appreciated for their strong semiconducting p-type properties related to van der Waals gaps and are at the forefront of new semi-conductor technology.

Interest in research on tellurides extends beyond the Earth, with the possible presence of a metallic ‘mist’ in the atmosphere on Venus which contains tellurium and volatile elements, including Pb, As, Sb and Bi, forming halides or chalcogenides with high vapour pressures (Schaefer and Fegley, 2004).

What is a gold-telluride deposit? – the starting point for IGCP-486

Lindgren (1933) introduced the subclass of “gold-telluride veins” as part of the epithermal deposit spectrum in his textbook “Mineral deposits”. Telluride-enrichment is, however, observed in a far wider range of deposit types, e.g., Au-rich VMS deposits, porphyry Au(Cu) and Au skarns. In at least some of these, a proportion of the gold occurs as Au-(Ag)-tellurides, or as native gold/Au-minerals paragenetically tied with tellurides of other elements, notably bismuth. Despite their enrichment in Te, gold deposits formed under reducing conditions are generally not acknowledged as Au-telluride deposits, because the telluride-rich character is largely expressed through an abundance of Bi-telluride species, commonly stable together with native bismuth. Gold-Bi compounds, such as maldonite and/or jonassonite, contribute to the mineralogical balance of gold ore, instead of Au(Ag)-tellurides (Ciobanu et al., 2005). A modified definition of the term ‘gold-telluride deposits’ was thus proposed (Cook and Ciobanu, 2005) to encompass the genetic connotation given by the presence of tellurides other than those of Au-Ag.

In a preface to a special issue of Mineralogy and Petrology, Ciobanu et al. (2006a) posed a series of questions concerning the ‘how?’ and ‘why?’ of gold-telluride deposit formation. They questioned some of the established thinking about how these deposits were understood, not because the ideas are wrong (on the contrary!), but to encourage debate, and look beyond the confines of what was known and which fitted well to certain epithermal deposits. Likewise, Cook and Ciobanu (2005) attempted to build a framework for the role of other types of hydrothermal systems in the generation of telluride-bearing deposits, raising certain taboos about classification, alternative settings and deposition mechanisms, the role of tellurides in orogenic gold systems and skarns, and what studies of trace mineralogy could contribute to the broader ore genesis perspective? They stressed the need to expand thermodynamic databases and modelling of ore-forming systems (Afifi et al., 1988; Zhang and Spry, 1994a; Simon et al., 1997) to cover a broader range of formation conditions, e.g., pH/eH variation vs. activity/fugacity of various aqueous/gas species in a hydrothermal system.

Within a given deposit, telluride-rich ores can be precipitated either at the same site or separately from native gold ore, depending upon precipitation mechanisms and local setting. Contemporary perspectives (e.g., Cooke and McPhail, 2001) include a Te-rich source, generally magmatically-derived, transport of Te as aqueous/vapour species within hydrothermal fluid, and precipitation of Au-Ag-tellurides due to multi-stage boiling. In an epithermal-porphyry environment (<5 km), these vapours are transported at the upper part of the veins forming a low-grade Au-Te cap on top of the main Au mineralisation underneath. Whereas this model fits some telluride-bearing Au deposits (e.g.,
Jensen and Barton, 2007) there are other examples of epithermal deposits for which this model is not suitable. Where can the model of Cooke and McPhail (2001) be applied? – does it always work? – can zonation always be expected?

Good examples also exist of telluride-bearing Au deposits formed in deeper (>5 km) settings, e.g., intrusion-related and orogenic gold deposits. For example, the giant Golden Mile deposit, Kalgoorlie (W.A.; Shackleton et al., 2003), which at 1,500 tonnes contained Au is the largest single lode gold system in the world. Whereas phase separation is commonly attributed to boiling in epithermal systems, this is associated with a catastrophic drop in fluid pressure in orogenic Au systems (Mikucki, 1998).

An association between alkaline magmatism and telluride-bearing epithermal mineralisation has often been assumed (e.g., Richards, 1995); many classic epithermal Au-Te systems (Cripple Creek, Emperor, Porgera, Ladolam and the Montana Au-Ag telluride belt) are associated with alkaline magmatism. Some such systems grade downwards into porphyry-type Cu-(Au) or Mo-(Au) deposits. Commenting on the association of tellurides with alkaline magmatism, Jensen and Barton (2000) emphasised that melting of Te-rich ocean floor sediments may be a key source of mantle-sourced alkaline magmas in subduction settings. Cook and Ciobanu (2005) and Ciobanu et al. (2006a) questioned whether the link to alkaline magmatism may have been overstated. Examples of telluride-enriched epithermal mineralisation in calc-alkaline volcanic rocks include the Baguio District, Philippines (Cooke and McPhail, 2001) and numerous Cretaceous-Quaternary deposits in Japan. The Golden Quadrilateral (Romania) and the Kurama Belt (Tien Shan, Uzbekistan), which both received attention during IGCP-486, are also associated with calc-alkaline volcanic rocks.

The present contribution summarises the main results of IGCP-486.

**Distribution of tellurides in gold provinces**

During the lifetime of the project, more than 100 occurrences worldwide were described and several key deposits and districts were visited (e.g., Golden Quadrilateral, Romania; Kurama belt, Uzbekistan; Cripple Creek, Colorado). More detailed work was carried out in the collage of terranes making up the European segment of the Tethyan belt, in Central Asia and in China (Fig. 1), even though other provinces including shield areas (e.g., Ukrainian and Fennoscandian Shields) also received coverage. The programme also included areas where less previous work was done on the telluride-selenide-bearing assemblages (e.g., epithermal deposits in the Bulgarian Rhodopes or porphyry/epithermal systems in Turkey).

**Cripple Creek, Colorado, USA**

Cripple Creek is a world-class, telluride-rich epithermal gold deposit (~28 Moz Au production) hosted by an Oligocene alkaline diatreme complex resulting from phonolitic lamprophyric magmatism (Kelley et al., 1998; Jensen, 2007; Jensen and Barton, 2007). The deposit features an outstanding mineralogy (Carnein and Bartos, 2005), with spectacular finds of telluride minerals during earlier mining. Gold mineralisation is mainly hosted by thin (typically <5 cm) seams of quartz. Intense potassium metasomatism was broadly developed throughout the diatreme which makes up the upper, explored part of the igneous complex. Ore-formation appears restricted to the latest stages of magmatism and many veins are characterised by a single stage of mineral deposition. Ore-forming fluids were dominated by low temperature (<225°C), dilute, CO₂-rich magmatically-derived fluids; phase separation by boiling and effervescence played key roles in gold precipitation. The abundance of tellurides at Cripple Creek is attributed to volatile-rich fluids associated with alkaline magmatism (Jensen and Barton, 2007).

**Emperor and Tuvatu deposits, Fiji**

The low-sulphidation epithermal gold-telluride deposit of Emperor, Fiji (11.5 Moz) is hosted by Late Miocene-Early Pliocene shoshonitic rocks and is one of the best studied examples (e.g., Pals and Spry, 2003; Pals et al., 2003). Although much of the gold occurs as invisible gold in pyrite, 10-50% of the gold occurs as telluride minerals.

The nearby Tuvatu deposit (Scherbarth and Spry, 2006) also contains a suite of unusual V-bearing minerals, including roscoelite and karelianite (Spry and Scherbarth, 2006). Thermodynamic calculations show that the stability fields of these minerals coincide with those of calaverite, the main gold telluride, and that V is likely derived from the same alkaline intrusive rocks, which are also considered as the source of Au and Te. These two gold telluride deposits, the largest in Fiji, are noted for their relatively high grades (~9 g/t Au), spatial association with the regional Viti Levu lineament, the Tuvau and Navilawa volcanic calderas, and low-grade porphyry copper mineralisation within the calderas (Begg, 2007; Spry, 2007). A direct relationship to volcanic calderas is also observed at Ladolam, Lihir Island (Carman, 2003).

**Peri-Tethyan domains in Europe (Alpine-Balkans-Carpathians-Dinarides)**

Magmatic belts in Peri-Tethyan domains in Europe (Alpine-Balkans-Carpathians-Dinarides) have provided much of the impetus for IGCP-486.

**Carpathians of Slovakia and Ukraine**

Neogene metallogenic provinces of central and eastern Slovakia has been an important source of precious and base metal ores for many centuries. The number of known occurrences of tellurides and selenides (Kremnica – where they are abundant, the Banská Štiavnica-Banská Hobruša ore district, Javorie Mts. and Zlatá Bana - Byšta deposits), confirm a widespread Te-signature. Despite this, the assemblages were only recently studied (Jelen et al., 2004; Maťo et al., 2006), enabling identification of new telluride species (e.g., within advanced-argillic type of alteration in the Vihrorlaitéský vrchy Mts.; Rídkošil et al., 2001; Skála et al., 2007). Occurrences in the Ukrainian Transcarpathians (e.g., Melnikov and Bondarenko, 2004; Melnikov et al., 2005) are of similar type.

**Golden Quadrilateral (Romania)**

The 900 km² Golden Quadrilateral, Romania (GQ), has a special place among telluride-bearing gold provinces (Cook and Ciobanu, 2004a and references therein). Mineralisation formed in a volcanic environment during Neogene calc-alkaline magmatism. The district
only contains a single deposit (Săcârîmb) in which Au-(Ag)-tellurides are the dominant ore minerals, but tellurides are common accessories in more than half the deposits and across the deposit spectrum - illustrated by the occurrence of tellurides in the giant Rosia Montana diatreme-hosted deposit (Cook and Ciobanu, 2004a; Tamas et al., 2006).

Tellurides can be used to decipher orefield zonation across porphyry-epithermal systems, e.g., in the Fata Baii–Larga orefield (Cook and Ciobanu, 2004b). Here, native gold and tellurides are present throughout the 1 km vertical extent of the hydrothermal system. Gold and Au-Ag tellurides are dominant at upper levels and Bi-tellurides at depth, with free gold in both associations. The deposit does not, therefore, follow the zonation model of Cooke and McPhail (2001) for epithermal gold-telluride deposits. The sulphidation reaction (löllingite + pyrrhotite → arsenopyrite + pyrite) recorded in the deeper part of the veins opened above an (immature) porphyry root, is considered the main process destabilising metal complexes in the fluid.

The model of Cooke and McPhail (2001) is also contradicted by the inverse zonation trends at Sacarîmb, a low-sulphidation (LS) epithermal deposit with no substantial evidence for boiling during vein formation (Alderton and Fallick, 2000). Here, telluride-rich ore forming the high-grade median part of the veins is situated underneath lower-grade native gold ore at the top. Observations of textures among telluride assemblages (Cook and Ciobanu, 2004a; Ciobanu et al., 2008) indicate deformation and overprinting during vein (re)opening. The position of the deposit, at the intersection of different fault systems, was optimal for development of sustained fluid throttling producing effervescence, probably the main mechanism of Au deposition at Sacarîmb.

**Banatitic Magmatic and Metallogenic Belt**

More than 50 porphyry, epithermal and skarn deposits occur within the Late Cretaceous Banatitic Magmatic and Metallogenic Belt (BMMB; Ciobanu et al., 2002a), southeastern Europe, the western-most portion of the Tethyan Eurasian Metallogenic belt (TEMB; Jankovic, 1997). The belt is one product of the subduction and obduction of ocean basins in the Tethyan region since the Mesozoic, as a result of the collision of Africa with Europe and other smaller microplates. The L-shaped belt extends from the North Apuseni Mountains (Romania) through the Timok region (Serbia), and across Bulgaria to the Black Sea. The eastern extension of the TEMB can be found in the Pontides of Turkey, and extends at least as far as Pakistan.

Although essentially a Cu-Au belt, the BMMB has a pronounced Bi-Te-signature, recognisable in styles of mineralisation ranging from skarns to porphyry and epithermal types. An association of Bi-tellurides with gold is evident even in cases where gold was neither exploited nor suspected (e.g., Ciobanu and Cook, 2004). The speciation of Bi-tellurides is dependent on the redox conditions. Assemblages differ markedly between skarns not associated with porphyries, many of which show reduced conditions with pyrrhotite and magnetite stable (e.g., Baisoara, Baita Bihor, Ocna de Fier), and porphyry Cu(Au) deposits (e.g., Moldova Novă) and Cu- or Zn-skarns associated with them (e.g., at Majdanpek), where oxidised assemblages with pyrite and hematite stable prevail (Ciobanu et al., 2003).

Gold-(Ag)-and Bi-tellurides are both reported from all deposit types in the Panagyurishte district (Bulgaria), demonstrating common fluid sources for the different mineralisation styles. The district contains porphyry (Elsatsite and Assarel) and epithermal deposits that range from high (Chelopech) to intermediate (Radka) and LS types (Elshitsa), (e.g., Bogdanov et al., 2004; 2005; Kozhuharova et al., 2005). Te-bearing species that are specific to the high sulphidation (HS) environment, such as goldfieldite, are present at Chelopech. The district includes PGE-bearing porphyry systems (e.g., Elatsite), where a telluride, merenskyite (PdTe2), is documented as the main PGE-carrier (Tarkian et al., 2003).
A telluride signature in the major epithermal, porphyry and skarn-type gold deposits of the eastwards extension of the belt is poorly documented (Bogdanov and Filipov, 2006), even if tellurides were occasionally reported (e.g., from the Murgul and Çayeli volcanogenic Cu deposits, Turkey; Zaykov et al., 2006).

The Hellenide tectonic collage

Work carried out in the Hellenides, part of the Alpine-Himalayan orogen, and formed when Apulia collided with Europe in the Late Cretaceous to Tertiary, is illustrative of the IGCP-486 approach to identify new areas characterised by telluride-bearing signatures (Fig. 2). In Greece, the tectono-structural collage comprises from NE to SW: the Rhodope (RM) and Serbomacedonian Massifs (SM), the Vardar Zone, the Pelagonian Zone and the Attico-Cycladic Massif (ACM, Internal Hellenides) and the External Hellenides built up by Mesozoic and Cenozoic rocks. Telluride enrichment occurs in three of these units: RM, SM and ACM and is found in both epigenetic deposits hosted in the metamorphic basement as well as in those affiliated with Tertiary-Quaternary magmatism.

In the SM, shear zone–hosted gold ores include both Ag-Au- and Bi-tellurides, e.g., at the Stanos/Chalkiudhi and Laodikino-Koronouda/Kilkis occurrences (Voudouris and Sakellaris, 2008). Gold mineralisation relates to late Cretaceous to Eocene crustal stretching and unroofing that produced shearing and flattening of the gneissic host rock at upper greenschist to amphibolite facies.

Tertiary epithermal and porphyry gold deposits in the RM include Au-Ag-tellurides. They relate to calc-alkaline to alkaline magmatism generated in a post-collisional setting. In addition, Bi-tellurides and -sulphosalts are noted in veins of HS-IS type (e.g., Viper, St. Demetrios, Kassiteres, Perama Hill, Pelka/Western Thrace; Voudouris, 2006; Voudouris et al., 2009). The RM also includes an example of a reduced intrusion-related gold (RIRG) system, e.g., Kavala (Melfos et al., 2008). Au-Bi-Te-Pb-Sb mineralisation occurs in sheeted quartz veins that crosscut the 21 Ma Kavala granodiorite and adjacent gneisses and marbles.

In the ACM, quartz veins hosted in Mesozoic marbles at Panormos Bay (Tinos island) and in metamorphic rocks of the Cycladic Blueschist Unit at Kallianou area (southern Evia island) contain electrum and a suite of Au-Ag (sulpho)tellurides (Tombros et al., 2004; 2007a,b; Voudouris and Spry 2008). At Panormos Bay, mineralisation relates to a 14 Ma, peraluminous leucogranite (Tombros et al., 2007b). At Kallianou, veins formed under ductile to brittle deformation in the footwall block of an exhumed metamorphic core complex and are discordant to syn-metamorphic structures. Both occurrences could be interpreted as RIRG systems. Gold-Ag tellurides are also present in volcanic-hosted epithermal veinlets crosscutting the Upper Pliocene Profitis Ilias pyroclastic cryptodome, Milos island, part of the active south Aegean volcanic arc (Alfieris and Voudouris, 2006a, b).

The telluride enrichment observed in deposits ranging from HS and LS epithermal to metamorphogenic gold systems in the Hellenides (Voudouris et al., 2007) may suggest that fluid sources are enriched in Te during mantle underplating and/or metasomatism. Further investigation is aimed at identifying whether this enrichment is due to several stages of remobilisation during successive accretion-extension episodes from Carboniferous to Pleistocene.

Tien Shan and Altaids, Central Asia

Tellurides and selenides are conspicuous components of several Paleozoic gold orefields of central Asia. In deposits of western Uzbekistan, such as Muruntau, Muytenbay, Charmitan and Gujumsay, they are restricted to Bi-bearing species (Koneev et al., 2005, 2008; Khalmatov, 2008; Mun, 2008).

Au(-Ag) tellurides are prominent in the Kurama belt, Middle Tien Shan, which hosts giant Au-Cu porphyry (e.g., Kalmakyr) and epithermal deposits associated with Paleozoic calc-alkaline volcanism. Many of the epithermal deposits (e.g., Kochbulak, Kayragach, Kyzylalmasay) are proper gold-telluride deposits and may contain a dozen or more different tellurides and selenides (Fig. 3). The speciation and relative proportion between tellurides and selenides provide clues to vertical zonation, e.g., Kyzylalmasay (Khalmatov, 2008). Selenides, especially those of Bi or Ag, are dominant at upper levels, whereas Ag-, Au-, Hg-, Sb-, Pb- and Bi-tellurides prevail at depth (Koneev et al., 2005; 2008). The evolution of telluride paragenesis with time in the Kochbulak and Kayragach deposits...
Episodes  Vol. 32,  no. 4

the Urals

Volcanic-hosted massive sulphide deposits in recrystallisation and coarsening of gold during late (low-temperature) tellurides within common sulphides may have, in part, resulted from have been reported, some of which may be significant gold-carriers. More than a dozen Au-Ag and Bi-bearing telluride species (e.g., Marcoux et al., 1996). The Urals province contains many known and can offer clues about deposit morphology and genesis sometimes Te-bearing. For example, telluride-rich stringer zones are among Au-(Ag)- and Bi-tellurides indicate the role of active tectonics in ore formation, as well as possible partial melting of a pre-existing ore (Ciobanu et al., 2006c), even if other workers (e.g., Kovalenker et al., 1997; Plotinskaya et al., 2006a) explain the same features via an explosive hydrothermal breccia model. Elsewhere in the central Asian Tian Shan-Altaid super-collision, other major deposits are equally well endowed with tellurides. Notable examples in Kyrgyz-stan include Kumor, possibly one of the largest tellurium-bearing deposits in the world, Jerooy, Taldy-baluk Levoberezhny and Nau-M (Djenchu-raeva, 2006). Jerooy is a low-sulphide tellurium-bearing deposit, e.g., Duolansayi (Xiao et al., 2008) and rezhny and Nau-M (Djenchu-raeva, 2006). Jerooy is a low-sulphide telluride deposit, particularly rich in tellurides. Au-Ag tellurides are telluride-rich stringer zones are common components of the ore. An outstanding example is the Chalkyruk skarn deposit where 80% of gold is present as tellurides. The Altaids of Xinjiang, China, represent an emerging telluride-bearing gold province, e.g., Duolansayi (Xiao et al., 2008) and several other recently-discovered deposits. Volcanic-hosted massive sulphide deposits in the Urals Volcanic-hosted massive sulphide (VHMS) deposits are sometimes Te-bearing. For example, telluride-rich stringer zones are known and can offer clues about deposit morphology and genesis (e.g., Marcoux et al., 1996). The Urals province contains many examples of Au-enriched VHMS systems that carry tellurides, e.g., Silurian-Devonian deposits at Safjanovsk, Uzelginsk, Gayskoye, Severo-Uvaryazhskoe, Tash-Tau, Babaryk, Yaman-Kasy, Spahyanovka, Valentorka and Alexandrinuskoye, which are representative of the different sub-types in the Uralian province (Vikentyev, 2006; Novoselov et al., 2006; Vikentyev et al., 2006; Maslennikova et al., 2008). More than a dozen Au-Ag and Bi-telluride telluride species have been reported, some of which may be significant gold-carriers. Vikentyev (2006) considered that the appearance of visible tellurides within common sulphides may have, in part, resulted from recrystallisation and coarsening of gold during late (low-temperature) hydrothermal processes and/or overprinting during prehnite-pumpellyite-greenschist facies metamorphism. Maslennikova et al. (2008) explained the abundance of tellurides and sulphosalts in the various chimney types in the Uralian VMS province, relative to Kuroko and Cyprus-type VHMS deposits, by sulphidation and/or oxidation during interaction of reduced hydrothermal fluids and oxidised seawater.

Belogub et al. (2008) report selenides from the supergene zones of the Gayskoye, Zapadno-Ozernoye, Dzhusinskoye and Alexandrinuskoye deposits. These result from liberation of Se from the common sulphides during oxidation and associated bacterial activity. Although mineralisation in the Urals is dominantly of VHMS type, tellurides are also prevalent in other types of deposit, e.g., orogenic or epithermal type. Precious metal tellurides occur, for example, in the Berezyanokskoe HS gold-telluride deposit, southern Urals (Plotinskaya et al., 2006b). This deposit was first described by Lehmann et al. (1999), with special emphasis on the gold-telluride connection.

Alpine-Yanshanian magmatism in China An increasing number of telluride-bearing gold deposits are known from China. These include deposits of intrusion-related, orogenic and epithermal type. Understanding the significance of the telluride-rich signature for both ore genesis and exploitation became clearer as a result of IGCP-486 (e.g., Mao et al., 2004; Zhao et al., 2005). Debate on telluride-bearing deposits from the northern margin of the North China Craton (NCC), e.g., Dongping, Huantualiang, Zhongshangou and Xiaoyinpan has centred on their origin as intrusion-related or orogenic deposits formed during multiple late Paleozoic–Mesozoic mineralizing events, and whether their association with alkaline magmatism carries genetic significance (e.g., Mao et al., 2003). Analogues on the southern margin of the North China Craton include Jingchangyu (Yanshan district) and Wulasan. The Pingyi area of western Shandong, on the southeastern margin of the North China Craton, is a second telluride-enriched gold province in China. Gold mineralisation relates to epithermal systems associated with the Early Jurassic Tongshi magmatic complex, e.g., Guilaizhuang, Lifanggou and Mofanggou (Hu et al., 2006). Fluid inclusion and isotope data for these deposits show that pressure release and fluid boiling, as well as fluid-rock interaction (Lifanggou and Mofanggou) and mixing of magnetically-derived fluids with meteoritic waters (Guilaizhuang) played an important role in ore formation.

The large Dashuigou Te-(Au) deposit, at the western margin of the Yangtze craton, Sichuan Province, is a spectacularly telluride-rich deposit interpreted as the product of a Permian large igneous province-related mantle plume (Chen et al., 1996; Mao et al., 1995; 2004; Zhao et al., 2005). Ores containing as much as 10 wt.% Te occur as veins within the metasalts.

Fennoscandian and Ukrainian Shields Tellurides and selenides can be conspicuous accessory minerals in gold deposits in Archaean or Proterozoic Shields. Bismuth and Te are useful pathfinder elements in exploration and tellurides have potential for understanding ore evolution. Deposits in such environments may be of orogenic type, but others are interpreted as metamorphosed VHMS, epithermal or porphyry deposits. From the 100 or so more important gold deposits in the Fennoscandian Shield (Sundblad, 2002), at least 38 contain Bi-
tellurides (selenides) (Ciobanu et al., 2004a). There exists a strong spatial and paragenetic link between gold and the presence of Bi-tellurides/selenides. Assemblages can be used to draw parallels between orefields situated in different units, such as between metamorphosed VHMS deposits at Falun (Bergslagen, Sweden) and Orijärvi-Hijärvi (Unisma Belt, SW Finland; Ciobanu et al., 2002b). Kojonen (2006) reviewed the main gold provinces in Finland, drawing attention to the Au-Ag selenide-telluride deposits: Orivesi (Kutemajärvi, Tampere schist belt), Jokisivu (Huitinen), the Ilomantsi gold showings and Pampamo test mine, Kylmäkangas (Orijärvi) and the Juomasuo gold deposit (Kuusamo). Kojonen (2006) considered all as metamorphosed epigenetic deposits occurring in shear zones with extensive alteration. Bi-tellurides are abundant in some ore pipes of the Orivesi deposit and in other deposits from the shield (e.g., Glava, Sweden), and may be significant Au-carriers (Cook et al., 2007d). Bismuth tellurides/selenides are also abundant in Au-Ag occurrences from Russian Karelia, e.g., in the 2007d; Ciobanu et al., 2009b). Bismuth tellurides/selenides are also abundant in the Juomasuo gold deposit (Kuusamo). Kojonen (2006) considered the Orivesi selenide-telluride deposits: Orivesi (Kutemajärvi, Tampere schist belt), Jokisivu (Huitinen), the Ilomantsi gold showings and Pampamo test mine, Kylmäkangas (Orijärvi) and the Juomasuo gold deposit (Kuusamo). Kojonen (2006) considered all as metamorphosed epigenetic deposits occurring in shear zones with extensive alteration. Bi-tellurides are abundant in some ore pipes of the Orivesi deposit and in other deposits from the shield (e.g., Glava, Sweden), and may be significant Au-carriers (Cook et al., 2007d; Ciobanu et al., 2009b). Bismuth tellurides/selenides are also abundant in Au-Ag occurrences from Russian Karelia, e.g., in the Raikkonkoski orogenic gold occurrence (Ivaschenko et al., 2007).

Syntheses of telluride occurrences in the Ukrainian Shield indicate the presence of Bi-tellurides within orogenic gold deposits, e.g., at Myaktske (Mudrovkska et al., 2004; Bondarenko et al., 2005).

Other areas

Another example of telluride-bearing hydrothermal systems associated with calc-alkaline magmatism resulting from IGCP-486 is the Tertiary Furthei Au deposit, Sardinia, Italy (Fadda et al., 2005a; b). Here, the system underwent evolution from an earlier intermediate sulphidation (IS) porphyry to an HS-epithermal system. Gold-Ag-tellurides are more abundant in deeper, sulphide-rich IS mineralisation; Te-bearing tetrahedrite and native tellurium appear stable in shallower, HS parts of the system dominated by enargite and luzonite. The Te content of tetrahedrite decreases away from the porphyry-style centre of the hydrothermal system.

Mineralogy was used to model Au-(Cu) skarn formation in the Rio Narceo Belt, northern Spain (Cepeda et al., 2006). Bi-tellurides and accompanying Au-minerals were shown to be efficient monitors of the oxidising state of the skarn systems at both Ortoesa and El Valle, with assemblages varying with the dominant Fe-sulphide or oxide.

Gold-(Ag) tellurides are widespread in magmatic provinces from Argentina (Paar et al., 2005) and are especially abundant in epithermal HS and LS deposits and they contribute to the precious metal grades (e.g., La Mejicana, Fatamata; Farallón Negro). Many of these deposits are genetically related to Miocene-Pliocene volcanism.

Among the many Au occurrences in southeastern B.C., Canada, that show RIRG affiliation is the CLY Group of prospects (Nelson district; Howard et al., 2007). Bi-tellurides and gold occur together in some of the sulphide-poor veins and the variation in Au contents in the Bi-tellurides, was interpreted to indicate zonation and/or overprinting during a later (orogenic?) episode (Cook et al., 2007c; Ciobanu et al., 2009b).

Telluride and selenide mineralization – new results

Telluride and selenide minerals – new data

New minerals described in the past six years include telluronevskite (Ridkošil et al., 2001), schlemaite, (Cu,□)₁₄(Ph,Bi)Se₄₋(Förster et al., 2003), mazzettiite, Ag₅HgPbSbTe₅ (Bindi and Ciobanu, 2004a), museumite, Pb₃AuS₈Te₄S₁₂ (Bindi and Ciobanu, 2004b), selenojapaite, Ag₄Cu₃Se₇ (Bindi and Pratesi, 2005), viharolattie (Skåla et al., 2007) and vavrinite, Ni₃Sb₂Te₅ (Lauluk et al., 2007). Although not a Te- or Se-bearing mineral, jonassonite, Bi₄Au₄S₄ (Paar et al., 2006) is always associated with Bi-chalcogenides.

Studies have generated new data on several Au-(Ag)-telluride minerals, including nagyágite (Ciobanu et al., 2008), empressite (Bindi et al., 2004), sylvanite (Cook and Ciobanu, 2004a), montbrayite (Shackleton and Spry, 2003), kostovite (Bonev et al., 2005) and cervelleite (see below). Reported unnamed phases include As-bearing Au-Ag-tellurides with empirical formulae (Ag₁₈Au₀₂₂)₁₂₀₈As₀₉₅Te₂ (Ciobanu et al., 2008) and (Au₁.₆₂Ag₈₃₉₃)₁₉₉₈As₁₀₈Pb₂₄Bi₈₉₆Te₁₇ₐ (Sung et al., 2007).

Nagyágite

Among the gold-tellurides, nagyágite, Pb₃(Ph,As)₆S₉ (Te,Ag), stands out in terms of its complex chemical-structural modularity combining (Au,Te) telluride layers stacked between 2x[Ph₃(As,Te)₆S₉] sulphosalts (Effenberger et al., 1999). Mineral modularity allows for chemical substitutions to be mapped onto structural sites, providing a petrogenetic tool. An example is the reinvestigation of material from the type locality (Săcărmăș, Romania), the only deposit where several compositional varieties of nagyágite are described (Ciobanu et al., 2008 and references therein). Their formation was interpreted in relation to pseudomorphic replacement during coupled dissolution reprecipitation reaction (CDRR) and linked to high fluid acidity. Replacement of nagyágite by galena-altaite symplectites is also attributed to CDRR, but instead reflects changes in fTe₂/fS₂ of a slightly alkaline fluid. A geological context for variation in fluid characteristics is provided by the reopening of veins during rotation of the duplex fault-system responsible for vein formation.

CDRR-assisted replacement of nagyágite by galena-altaite symplectites is also reported from the Sunrise Dam orogenic Au deposit, Yilgarn Craton, Western Australia (Sung et al., 2007). No compositional variation is seen, inferring unchanged fluid composition during syn-deformational overprinting. Precipitation of native gold, retained within the symplectites, accompanies destabilisation of nagyágite.

Cervelleite

Cook and Ciobanu (2003a) summarised published data for cervelleite, and added new data from skarn (Ocna de Fier and Baita Bihor) and epithermal (Larga) occurrences in Romania. Cervelleite, ideally Ag₁₉Te₅, may incorporate significant Cu, within the range Ag₃Te₅ to approximately (Ag₃Cu₅)₃Te₅. An additional phase, Ag₃Cu₅Te₅, possibly the first quartary phase in the system Ag₃Cu₁₅Te₅S, was identified in two occurrences. Cervelleite from VHMS deposits in the southern Urals shows comparable levels of Cu-for-Ag substitution; several unnamed mineral species are also present (Novoselov et al., 2006). The latter are distinguished, not only by variable Cu contents, but also by Te/S ratios that depart from the 1:1 ratio in cervelleite, or by apparent cation deficiencies. Other unnamed Ag-Cu sulphophiyl tellurides were described from Greece: [(Ag,Cu)₅Te₅S₇] and Ag-Au-Cu [(Ag,Au,Cu)₅Te₅S₇] or [(Ag,Cu),Au,Te₅S₇] from Tinos Island (Tombros et al., 2004) and Ag₃Cu₁₅Te₅S and (Ag,Cu)₅Te₅S
from Kallianou (Voudouris and Spry, 2008). Compositional variation among phases of the cervelleite group may be yet another case to explore further as a source of petrogenetic information. For example, in skarns, these minerals are part of broader ‘exotic’, volatile-rich mineral parageneses tracing retrograde stages (Cook and Ciobanu, 2001, 2003b; Ciobanu and Cook, 2000, 2004; Ciobanu et al., 2004b).

**Bismuth and bismuth-lead tellurides**

*The tetradymite group*

Bismuth tellurides (as well as selenides, tellurosulphides and telluroselenides) are prominent components of many gold deposits (Fig. 4). They are grouped in a homologous series of mixed-layer compounds with rhombohedral or trigonal symmetry derived from a 5-layer $X$-$Bi$-$X$-$Bi$-$X$ module ($X=Te$, $Se$, $S$), known as the ‘tetradymite archetype’, by incremental addition of $Bi$-$Bi$ leading to the structural formula $nBi_2mBi_2X_3$ ($n=$ number of $Bi$ units; $m=$ number of $Bi_2X_3$ units; Cook et al., 2007a). This type of modular structure enables any discrete composition in the interval $Bi_2X_3$-$Bi$ to be represented by a specific stacking sequence. Each stoichiometry ($Bi$:X ratio) within the group (e.g., $Bi_2Te_3$, $Bi_4Te_3$) represents an isoseries – e.g., tellurobismutite $Bi_2Te_3$, tetradymite $Bi_2Te_2S$, kawazulite $Bi_2Te_2Se$). Ciobanu et al. (2009a) used high-resolution transmission electron microscopy (HR-TEM) to study compounds in the compositional range $Bi_2Te_3$-$Bi_8Te_3$. Although the $Bi_2$ and $Bi_2X_3$ units can be imaged, they do not underpin homology in the group. Instead, the layer-modules and homology are defined by the structural formula $S'(Bi_2kX_3)L'(Bi_2(k+1)X_3)$ ($X=$ chalcogen; $S'$, $L'$=number of short and long modules, respectively); all phases are $N$-fold ($N$=total number of layers in the stacking sequence) superstructures of a rhombohedral subcell.

Such a formula provides an easy method for calculation of the stacking sequences from electron diffractions and their simulation using computer software (MSCG, appendix to Ciobanu et al., 2009a). This further allows for definition of single phases from random polysomes and thus assists with establishing equilibrium vs. disequilibrium during crystallisation. This is an important step in analysing naturally-occurring ‘minerals’ from the series that often may contain variable lengths of polysomes embedded in the stacking sequences (Ciobanu et al., 2010). An illustration of this approach is shown for tsumoite ($BiTe$) from the type locality in Fig. 5.

*The ‘aleksite’ series*

A second homologous series of $Bi$-$Pb$-compounds that can be derived from the same ‘tetradymite’ archetype by adding $Pb(Bi)$-$X$ instead of $Bi$-$Bi$ layers ($X=$ chalcogen), is informally known as the ‘aleksite’ series (Cook et al., 2007b; Ciobanu et al., 2009a). They are found almost exclusively within Au-bearing deposits. Structures of compounds from the two series that have the same number of individual layers ($N$) are isoconfigurational one with another. Mölo et al. (2008) classify these phases within the broader family of sulphosalts despite the fact that their structures feature $X$-$X$ bonds, one of the forbidden characteristics in this group.

**Phase systems and constraints on mineral stabilities**

Despite the wealth of data compiled by Afifi et al. (1988), construction of phase diagrams to represent observed assemblages in many tellurium-bearing systems remains difficult due to the lack of reliable thermodynamic data for some minerals. New data for the system Ag-Au-X ($X=S$, $Se$, $Te$) (Echmaeva and Osadchii, 2008) is thus welcome, as are improved thermodynamic data for the systems $Au-Te$ (Wang et al., 2006), $Au-Bi-Sb$ (Wang et al., 2007) or the systems $Au-Bi$ and Ag-Au-Bi (Servant et al., 2006; Zoro et al., 2007), the last four allowing greater accuracy in modelling the critical system $Au-Bi-Te$ (Wagner, 2007; Tooth et al., 2008; see below). Fundamental thermodynamic information for Se-bearing systems has also become available (e.g., Xiong, 2003; Akinfiev and Tagirov, 2006a; b; Osadchii and Echmaeva, 2007), allowing detailed modelling of, for example,
features are, however, often obliterated by exsolution and recrystallisation of tellurides (e.g., Zhang and Spry, 1994b; Spry et al., 1997, Shackleton et al., 2003; Scherbarth and Spry, 2006). Put simply, observed assemblages are the final result of a protracted history of crystallisation during cooling and are often complicated by overprinting events.

Confirming the predictions of Cabri (1965) for the system Au-Ag-Te, observation of calaverite–sylvanite–hessite (Golden Mile deposit, Kalgoorlie, Western Australia) has shown that calaverite–hessite is a non-equilibrium assemblage, whereas hessite–sylvanite is the stable one, and results, via stützite, from the breakdown of the higher-temperature (>300°C) metastable â- or ÷-phases below 120°C (Bindi et al., 2005). The debated sylvanite–hessite-petzite triple-point (Prince et al., 1990) has been observed in Săcârîmb (Ciobanu et al., 2008) and obtained in experiments using solid-state galvanic cell electrochemical methods (Echmaeva and Osadchii, 2008).

**Figure 5. Characterisation of tsumoite from Tsumo (Japan) using electron diffraction and high-resolution transmission electron imaging (HR-TEM).** This work was done on a TEM foil (inset on a) prepared by Focused Ion Beam (FIB) methods using a FEI Helios nanoLab DualBeam FIB/SEM system, AMMRF, Adelaide. (a) Electron diffraction pattern (EDP) on [110]_h zone axis. Four-integer (hkl:m) indexation is with respect to hexagonal cell setting (subscript h; 4D group P-R3;m11; Lind and Lidin, 2003). The modulation vector (q; arrow) is used to index the superstructure reflections (see Ciobanu et al., 2009a). The strip underneath shows the d* (corresponding to d~0.2 nm) interval between two main reflections along (0001) rows. The smallest distance (arrows) between two superstructure reflections corresponds to (1/12)d* indicating a 12-fold superstructure (total number of layers in the unit cell N =12). (b) HR-TEM images at different defocus indicating a 12-fold superstructure reflections along (000l) rows. The smallest distance (arrows) between two superstructure reflections corresponds to (1/12)d* indicating a 12-fold superstructure (total number of layers in the unit cell N =12).

### Petrogenetic implications and new ideas

#### Melt scavengers for gold

A recent breakthrough idea is the recognition of the role of low-melting-point chalcophile elements (LMCE; Frost et al., 2002) in assisting Au-enrichment in ores. Partial melting of a sulphide ore is achieved, for example, if it undergoes metamorphism at temperatures above the melting-point of some of the contained ore minerals. The LMCE group includes elements which commonly occur in remobilised assemblages (Bi, Sb, As, Te etc.), and which form chalcogenides (sulphosalts and tellurides,selenides). The importance of LMCE melts lies in the fact that they can act as scavengers for Au, a metal that otherwise has a high melting-point. Generation of Bi-rich melts can be initiated at conditions as low as upper greenschist facies (Highi Massif, Romania; Ciobanu et al., 2006b). Tomkins et al., (2007) provided a comprehensive study of phase diagrams showing the conditions at which anatexis is initiated for various LMCE polymetallic melts.

The idea that melts can be precipitated directly from hydrothermal fluids and thus provide a more efficient mechanism of Au scavenging from those fluids than the commonly invoked ‘precipitation upon saturation’ process, has been tested experimentally for melts from the Au-Bi system (the ‘Bi-melt collector model’; Douglas et al., 2000). In this case, the crystallisation products should include phases formed along a solvus ending with eutectic assemblages in a given LMCE system, at the lower temperature limit. As discussed by Ciobanu et al. (2005) formation conditions of many deposit types, in particular skarn, intrusion-related and orogenic Au, overlap with the temperature range (234-475°C) of the 10 eutectics in the Au-Bi system; 8 of the eutectics include gold minerals. Annealing-quenching experiments, using telluride assemblages from the systems Au-Ph-Te and Au-Bi-Te in representative epithermal and intrusion-related ores from Musariu (Romania) and Oya (Japan), respectively, were undertaken to test models involving eutectic crystallisation from these LMCE systems (Ciobanu et al., 2007a, b). Wagner (2007) and Tooth et al. (2008) provided thermodynamic modelling of Au-Bi-Te and Au-Bi melts, respectively, co-existing with hydrothermal fluids. Both models show the efficiency of such melts for extracting Au even from fluids undersaturated in this element.

Applications of the melt model include: intrusion-related gold
Can tellurium assist incorporation of gold into pyrite?

Invisible gold includes both lattice-bound gold and sub-microscopic inclusions of gold minerals in common sulphides, e.g., pyrite and arsenopyrite. Gold-bearing pyrite is commonly As-bearing, leading to a paradigm for gold trapped in pyrite in which As is considered essential for Au to enter the pyrite structure (e.g., Reich et al., 2005). The highest gold concentration (~1 wt.%) measured in arsenian pyrite is from Emperor, Fiji (Pals et al., 2003) but in this case, there is also a stronger correlation between gold and tellurium. Can Te-bearing, As-free pyrite carry gold?

A LA-ICP-MS study of invisible gold in pyrite from the Dongping and Huanthanling deposits, Hebei Province, China (Cook et al., 2009) confirms this to be the case. Superimposed microshearing and fracturing/brecciation and pyrite recrystallisation control the distribution of invisible gold in As-free pyrite in a telluride-bearing mineralised system, with highest gold values in pyrite (up to 1 wt.%) correlating with clustering of telluride inclusions. Textural and LA-ICP-MS data suggest that the distribution of telluride inclusions extends from micron- to nanoscale, including that lattice-bound gold is present, correlating strongly with Te. It was concluded that tellurium and other “LMCE” that form tellurides (e.g., Ag, Pb, Cu, Bi) play a role in governing gold distribution patterns during the protracted geologic history. Transient porosity developed during CDR affecting pyrite could provide sites of precipitation for the clustered (nano)particles; Au and LMCE were either remobilised from the initial pyrite or introduced from the fluid.

In a recent study of arsenian pyrite textures correlated with zonation trends in sediment-hosted gold deposits affected by metamorphism, has shown that weakly-bonded elements include Te and Bi and are released during pyrite recrystallisation (Large et al., 2009).

Bi-chalcogenides as gold-carriers

The paragenetic association of gold minerals with Bi-tellurides and -sulphosalts led Ciobanu et al. (2009b) to assess whether Bi-chalcogenides might carry gold. In-situ laser-ablation inductively-coupled mass spectroscopy (LA-ICPMS) analysis of a range of Bi-chalcogenides from 28 worldwide occurrences (including epithermal, skarns, intrusion-related and orogenic gold) has shown that they can indeed carry gold at concentrations of up to thousands of ppm (in the same range as arsenian pyrite). Hitherto-neglected gold locked within these minerals can contribute to low gold recoveries in deposits in which these minerals are abundant. Trace element trends suggest that Au incorporation is underpinned by statistical substitution of Ag and Pb into the Bi octahedron in the Bi-telluride structures. Gold entrainment may also be linked to the presence of Van der Waals bonds at chalcogen-chalcogen contacts (Ciobanu et al., 2009a), which act as structural traps for gold nanoparticles. Altaite (PbTe) is also identified as a Au carrier (Vikentyev, 2006; Ciobanu et al., 2009b).

Ciobanu et al. (2009b) have also shown that trends of Au content in Bi-chalcogenides, if well understood in the context of phase relationships, are useful to define field zonation, overlapping events and allow discrimination between processes involving equilibrium or disequilibrium, i.e., crystallisation from melts or scavenging from fluids, respectively.

Concluding remarks

1. Whereas telluride/selenide-trace mineralogy is widespread in deposits of many types (MVT deposits are a notable exception), deposits in which Au(Ag)-tellurides form a part of the exploitable ore, are appreciably rarer (only some dozens are known at present).
2. Although Te and Se are both chalcophile elements and share a geochemical affinity with Au, they occur together mainly when Ag and/or Bi are present (e.g., phases from the tetradymite and/or aleksite groups). Formation of selenides of other elements such as Cu or Ag requires acidic (e.g., high-sulphidation systems) or reducing environment (e.g., black shales, uranium deposits).
3. Telluride-rich gold deposits, in which Au(Ag)-tellurides are typical species, stand out as ‘mineralogical anomalies’ (>10 different Te- and/or Se-bearing species present). Such deposits can be related to specific metallogenetic environments. Known deposits fall broadly into two categories with respect to tellurium source:
   a. Deposition from Te-rich fluids generated in specific local and/or regional settings, e.g., Te-enrichment in the mantle where alkaline magmas are generated, due to subduction of Te-rich ocean-floor sediments, as seen around the Pacific Rim.
   b. Deposition from Te-bearing fluids, where the concentration of Te would normally result in, at best, generation of a Te-enriched trace telluride signature, but where destabilisation and co-precipitation of Te with Au(Ag)-species from the fluids is enhanced by the action of sustained phase-separation processes in a depositional trap, e.g., fault-valve mechanism, one of the tectonic models for orogenic gold systems (at Golden Mile, Kalgoorlie, W.A. or Ilomantsi and Pampalo, Finland, etc.). The same mechanism may operate during duplex-fault rotation which controls formation of the epithermal vein-mesh in the buried volcano at Sácárim (Romania). In the absence of a depositional trap, formation of low-grade Te-Au(Ag)-rich caps at the top of gold systems is, instead, predictable.
4. Considering the vapour-phase affinity of Te, pressure-variation or multistage boiling processes rather than fluid-rock interaction, cooling or mixing, are more likely to fulfil the conditions required under point 3b. Vapour-phase release during magmatic brecciation is another viable scenario. This has been invoked by some authors for bonanza pipes at Kochbulak (Uzbekistan) and also for telluride-rich breccia pipes at Cripple-Creek (USA).
5. The convergence between the thermodynamic stability conditions for Au- and Ag-tellurides and native tellurium with those offered by an epithermal environment (hematite, pyrite stability; high
Figure 6. Diagrams in loga O₂ vs. pH space showing the coincidence between the stability fields of Te-Au-Ag-Bi-minerals and iron sulphides/oxides, and related aqueous species, at 251°C. (a) Te-bearing minerals (native tellurium, calaverite (Au₂Te) and the phase Ag₁.₆₄Te (~stützite); (b) Fe-bearing minerals (pyrite, hematite, magnetite and pyrrhotite); (c) Au-bearing minerals (native gold, maldonite (Au₂Bi) and calaverite); and (d) Bi-bearing minerals (native bismuth, bismuthinite and maldonite). Conditions: loga Au⁺ = -9 (on a), -6 (on c) and -10 (on d); loga Bi(OH)₃ (aq) = -12 (on c) and -6 (on d); loga H₂TeO₃ (aq) = -3 (on a) and -12 (on c); Ag⁺ = -15 (on a); loga Cl⁻ = -1; loga H₂O = 0; loga SO₄²⁻ = 0 and loga Fe²⁺ = 0. These conditions were chosen to illustrate the appearance of Te-, Au-, Ag- and Bi-minerals as discussed in the text. Note that at sulphur concentrations high enough to show an extended pyrite field in (b), the species Au(HS)₂⁻ and bismuthinite also have large stability fields (on c and d, respectively). An arbitrary pressure of 500 bar is taken. The pyrite field (in green) from (b) is superimposed on the other diagrams. Note the broad overlap between pyrite and calaverite in (a) and (c), and between pyrite and bismuthinite in (d). In (a), tellurium is stable at more oxidizing conditions than calaverite, plotting at the upper limit of pyrite and extending into the hematite field. In the presence of Bi (c and d), maldonite and bismuth are stable at more reducing conditions (pyrrhotite and magnetite fields). At loga SO₄²⁻ = 0 used for the diagrams, bismuthinite is stable. Thermodynamic data used for Au-, Bi- and Te-minerals and species, except for native Au, derive from the updated thermodynamic database of the Minerals, Metals and Solutions Group, South Australian Museum; see also data depository in Tooth et al. (2008) for maldonite and bismuthinite. Data for native Au and iron minerals are from the GWB default database (thermo.com.V8.R6), oct94. Since Bi-tellurides are not included in the database, they are not shown on diagrams (a) and (d); work is in progress to address this.
oxidation state; Fig. 6a-c) explains the greater abundance of Au-telluride deposits in such geological settings. Similar neutral to weakly-alkaline pH, low-salinity fluids are also typical for orogenic gold systems, especially at epithermal to mesozonal crustal levels, e.g., Sunrise Dam, Golden Mile, Kalgoorlie (Western Australia).

6. Telluride-rich gold deposits in which phases from the tetradymite group (those with Bi(Te,Se,S)) are the dominant tellurides, and these co-exist with Au-Bi compounds (maldonite and jonassonite) instead of Au(Te)-tellurides, are constrained to reduced depositional environments (pyrrhotite, magnetite stability; low oxidation state). Native bismuth and maldonite are stable at reduced conditions (Fig. 6b-d). This is often concordant with conditions attained during fluid-rock interaction, mixing or discharge at redox fronts, processes that are most typical during stages of gold deposition in skarns and intrusion-related gold deposits, as well as in some orogenic gold and VHMS systems.

7. Tellurides represent ideal melt scavengers for gold, if LMCE melts are either exsolved directly from hydrothermal fluids or are formed during metamorphic deformation. Coupled dissolution-reprecipitation reactions, if assisted by LMCEs, will lead to crystal-scale remobilisation of gold within Au carriers such as pyrite, even in the absence of As, e.g., in the aforementioned Chinese deposits. Gold remobilises with LMCE-rich signatures are present, for example, in metamorphosed deposits of different genetic types including VHMS, throughout the Fennoscandian Shield.

8. Comparative analysis of paragenesis, textures and compositional variation in tellurides/ tellurides, especially those with crystal-structural modularity, has an hitherto unexploited petrogenetic potential to reveal: (i) interaction with fluids, e.g., Au scavenging and entrapment in Bi(Pb)-tellurides; (ii) changes in the chemistry/ rates of fluid infiltration, e.g., nargyáite; (iii) equilibrium state in a given assemblage, e.g., homology in the tetradymite group.

dissolution-reprecipitation reactions, if assisted by LMCEs, will lead to crystal-scale remobilisation of gold within Au carriers such as pyrite, even in the absence of As, e.g., in the aforementioned Chinese deposits. Gold remobilises with LMCE-rich signatures are present, for example, in metamorphosed deposits of different genetic types including VHMS, throughout the Fennoscandian Shield.

Acknowledgements

We gratefully acknowledge the support and enthusiasm of IUGS and UNESCO who funded the project via the IGCP scheme, enabling many individuals to attend project events. We also very much thank all the organisations, associations and mining companies which provided IGCP-486 with additional financial support – especially those which kindly hosted or sponsored our field trips and project publications, or underwrote IGCP-486 events. CLC acknowledges funding through ARC ‘Discovery’ grant DP0560001. We gratefully acknowledge the support of the Australian Microscopy and Microanalysis Research Facility (AMMRF) for use of the FEI Helios nanoLab DualBeam FIB/SEM system at Adelaide Microscopy. The Minerals, Metals and Solutions Group, South Australian Museum, is kindly thanked for access to their updated thermodynamic database for Fig.6. We thank Bernd Lehmann for his expert review and Prof. M. Jayananda for his efficient editorial handling of the manuscript. This is TRaX contribution no. 41.

References

Afifi, A.M., Kelly, W.C., and Essene, E.J., 1988, Phase relations among tellurides, sulfides, and oxides: I. Thermochemical data and calculated equilibria; II. Applications to telluride-bearing ore deposits: Economic Geology, v. 83, pp. 377-394 and 395-404.

Akinfiev, N.N., and Tagirov, B.R., 2006a, Effect of selenium on silver transport and precipitation by hydrothermal solutions: Thermodynamic description of the Ag-Se-S-Cl-O-H system: Geology of Ore Deposits, v. 48, pp. 402-413.

Akinfiev, N.N., and Tagirov, B.R., 2006b, The role of selenium in hydrothermal transport of Au, Ag, and Cu: quantum chemical and thermo-dynamic evaluation: 12th Quadrennial IAGOD Symposium, Moscow, Extended abstract CD-ROM, abstract 310, 5 pp.

Alderton, D.H.M., and Fallick, A.E., 2000, The nature and genesis of gold-silver-tellurium mineralization in the Metalliferi Mountains of western Romania: Economic Geology v. 95, pp. 495-515.

Alfileris, D., and Voudouris, P., 2006a, First occurrence of tellurides in the epithermal Profitis Bias deposit, Milos Island, Greece: 12th Quadrennial IAGOD Symposium, Moscow, Extended abstract CD-ROM, abstract 318, 6 pp.

Alfileris, D., and Voudouris, P., 2006b, Tellurides and sulfosalts in the shallow submarine epithermal deposits of Milos Island, Greece: Proceedings, Field Workshop of IGCP-486, 24-29th September 2006, Dokuz Eylul University, Izmir, Turkey, pp. 6-14.

Begg, G., 2007, Gold and tectonics: A dynamic link. Ores and Ore Genesis 2007: Circum-Pacific Tectonics, Geologic Evolution, and Ore Deposits Symposium, Program with Abstracts, No. 108.

Belougub, E.E., Novoselov, K.A., Yakovleva, V.A., and Spiro, B., 2008, Supergene sulphides and related minerals in the supergene profiles of VHMS deposits from the South Urals: Ore Geology Reviews, v. 33, pp. 239-254.

Bindi, L., and Cipriani, C., 2004a, Mazzettitite, Ag,HgPbSbTe₇, a new mineral species from Findlay Gulch, Saguache County, Colorado, USA: Canadian Mineralogist, v. 42, pp. 1739-1743.

Bindi, L., and Cipriani, C., 2004b, Museumite, Pb₅AuSbTe₁₂, a new mineral from the gold-telluride deposit of Sacarimb, Metalliferi Mountains, western Romania: European Journal of Mineralogy, v. 16, pp. 835-838.

Bindi, L., and Pratesi, G., 2005, Selenojalpaite, Ag₃CuSe₂, a new mineral species from the Skrikerum Cu-Ag-Tl selenide deposit, Småland, southeastern Sweden: Canadian Mineralogist, v. 43, pp. 1373-1378.

Bindi, L., Spry, P.G., and Cipriani, C., 2004, Empressite, AgTe, from the Empress-Josephine mine, Colorado: Composition, physical properties and determination of the crystal structure: American Mineralogist, v. 89, pp. 1043-1047.

Bindi, L., Rossell, M.D., Van Tendeloo, G., Spry, P.G., and Cipriani, C., 2005, Inferred phase relations in part of the system Au-Ag-Te: an integrated analytical study of gold ore from the Golden Mile, Kalgoorlie, Australia: Mineralogy and Petrology, v. 83, pp. 283-293.

Bogdanov, K., Ciobanu, C.L., and Cook, N.J., 2004, Bi-Te-Se and PGE associations of gold in the Upper Cretaceous Banatitic Magmatic and Metallogenic Belt: 32nd International Geological Congress, Florence, Italy, CD-ROM Abstract volume, part 1, abstract 54-25, p. 276.

Bogdanov, K., Filipov, A., and Keyayov, R., 2005, Au-Ag-Te-Se minerals in the Elatsite porphyry-copper deposit, Bulgaria: Geochemistry, Mineralogy and Petrology, v. 43, pp. 13-19.

Bogdanov, K., and Filipov, A., 2006, Bi-Te mineral assemblages of gold in porphyry-epithermal systems: examples from the western segment of the Tethian-Eurasian copper belt. Proceedings, Field Workshop of IGCP-486, 24-29th September 2006, Dokuz Eylul University, Izmir, Turkey, pp. 15-22.

Bondarenko S., Grinchenko O., and Semka V., 2005, Au-Ag-Te-Se mineralization in the Potashnya gold deposit, Kocherov tectonic zone (Ukrainian Shield): Geochemistry, Mineralogy and Petrology, v. 43, pp. 20-25.

Bonev, I.K., Petrunov, R., Cook, N.J., and Ciobanu, C.L., 2005, Kostovite and its argentian varieties: Deposits and mineral associations: Geochemistry, Mineralogy and Petrology, v. 42, pp. 1-22.
Cabri, L.J., 1965. Phase relations in the Au-Ag-Te system and their mineralogical significance: Economic Geology, v. 60, pp. 1569-1606.

Carman, G.D., 2003. Geology, mineralization, and hydrothermal evolution of the Ladolam gold deposit, Lihir Island, Papua New Guinea: Society of Economic Geologists Special Publication 10, pp. 247-284.

Carnein, C.R., and Bartos, P.J., 2005. The Cripple Creek mining district: Mineralogical Record, v. 36, pp. 143-185.

Cepeda A., Fuertes-Fuente M., Martin-Izard A., Gonzalez-Nistal S., and Rodriguez-Pevida L., 2006, Tellurides, selenides and Bi – mineral assemblages from the Ryo Narcea Gold Belt, Asturias, Spain: genetic implications in Au-Au and Au skams: Mineralogy and Petrology, v. 87, pp. 277-304.

Chen, Y., Mao, J., Luo, Y., Wei, J., Cao, Z., Yin, J., Zhou, J., and Yang, B., 1996. Geology and geochemistry of the Dashaiquiu tellurium (gold) deposit in western Sichuan, China: Atomic Energy Press, Beijing, pp. 99-106. (in Chinese).

Ciobanu, C.L., and Cook, N.J., 2000, Intergrowths of bismuth sulphosalts from the Ocna de Fier Fe-skarn deposit, Banat, Southwest Romania: European Journal of Mineralogy, v. 12, pp. 899-917.

Ciobanu, C.L., and Cook, N.J., 2004, Skarn textures and a case study: the Ocna de Fier-Dognecea orefield, Banat, Romania: Ore Geology Reviews, v. 24, pp. 315-370.

Ciobanu, C.L., Cook, N.J., and Stein, H., 2002a, Regional setting and geochronology of the Late Cretaceous Banatitic Magmatic and Metallogenic Belt: Mineralium Deposita, v. 37, pp. 541-567.

Ciobanu, C.L., Cook, N.J., and Sundblad, K., 2002b, Genetic insights from exotic trace mineral associations at Orijirijü and IIijirijü, S.W. Finland. in: Metallurgy of Precambrian Shields: Ky'iv, Ukraine, September 2002. Abstract volume, pp. 41-45.

Ciobanu, C.L., Cook, N.J., Bogdanov, K., Kiss, O., and Vučković, B., 2003, Gold enrichment in deposits of the Banatitic Magmatic and Metallogenic belt, in: Eliopoulos, D.G et al., eds, Mineral Exploration and Sustainable Development. Millpress, Rotterdam, pp. 1153-1156.

Ciobanu, C.L., Cook, N.J., Sundblad, K., and Kojoenen, K., 2004a, Tellurides and selenides in Au ores from the Fennoscandian Shield: A status report: 32nd International Geological Congress, Florence, Italy, CD-ROM Abstract volume, part 1, abstract 54-12, p. 274.

Ciobanu, C.L., Pring, A., and Cook, N.J., 2004b, Micron- to nano-scale intergrowths among members of the cuprobismutite series and padraite: HRTEM and microanalytical evidence: Mineralogical Magazine, v. 68, pp. 279-300.

Ciobanu, C.L., Cook, N.J., and Pring, A., 2005, Bismuth tellurides as gold scavengers, in: Mao, J.W. and Bierlein, F.P. eds, Mineral Deposit Research: Meeting the Global Challenge Springer, Berlin-Heidelberg-New York, pp. 1383-1386.

Ciobanu, C.L., Cook, N.J., and Spiry, P.G., 2006a, Preface – Special Issue: Telluride and selenides minerals in gold deposits – how and why? Mineralogy and Petrology, v. 87, pp. 163-169.

Ciobanu, C.L., Cook, N.J., Damian, F., and Damian, G., 2006b, Gold scavenged by bismuth tellurides: An example from Alpine shear-remobilisates in the Highe Massif, Romania. Mineralogy and Petrology, v. 87, pp. 351-384.

Ciobanu, C.L., Cook, N.J., Koneev, R., and Damian, G., 2006c, Significance of tellurides in understanding formation of Au mineralisation: A comparison between Au-telluride deposits at Sacarim, Romania, and Kochbulak, Uzbekistan. Joint IGCP-473 and -486 Workshop 'Porphyry deposits of the Cripple Creek mining district: Ore Geology Reviews, v. 24, pp. 315-370.

Ciobanu, C.L., Cook, N.J., Mavrogenes, J., Damian, G., and Damian, F., 2007a, Au-Pb-Te melts: Annealing-quenching experiments on samples from the Musaria gold deposit, Brad District (Romania): Proceedings, Field workshop of IGCP-486, Espoo, Finland, August 26th-31st 2007. Geological Survey of Finland Opas v. 53, pp. 5-13.

Ciobanu, C.L., Mavrogenes, J., Cook, N.J., and Shimizu, M., 2007b, Au-Bi-Te melts: Annealing-quenching experiments on samples from the Oya deposit (Japan). Proceedings, Field workshop of IGCP-486, Espoo, Finland, August 26th-31st 2007: Geological Survey of Finland Opas, v. 53, pp. 5-13.

Ciobanu, C.L., Mavrogenes, J., Cook, N.J., and Shimizu, M., 2007a, Au-Ag-Telluride and selenides minerals in gold deposits – how and why? Mineralogy and Petrology, v. 87, pp. 351-384.

Cook, N.J., and Ciobanu, C.L., 2003a, Cervelleite, Ag4TeS, from three localities in Romania, substitution of Cu, and the occurrence of the associated phase, Ag2Cu2TeS: Neues Jahrbuch für Mineralogie Monatshefte, pp. 321-336.

Cook, N.J., and Ciobanu, C.L., 2003b, Lamellar minerals of the cuprobismutite series and related padraite: a new occurrence and implications: Canadian Mineralogist, v. 41, pp. 441-456.

Cook, N.J., and Ciobanu, C.L., eds., 2004a, Gold-Silver-Telluride Deposits of the Golden Quadrilateral, South Apuseni Mts., Romania: IAGOD Guidebook Series, v. 12, 266 pp.

Cook, N.J., and Ciobanu, C.L., 2004b, Bismuth tellurides and sulphosalts from the Larga hydrothermal system, Metaliferi Mts., Romania: Paragenesis and genetic significance: Mineralogical Magazine, v. 68, pp. 301-321.

Cook, N.J., and Ciobanu, C.L., 2005, Tellurides in Au deposits: implications for modelling, in: Mao, J.W. and Bierlein, F.P. eds,Mineral Deposit Research: Meeting the Global Challenge: Springer, Berlin-Heidelberg-New York, pp. 1387-1390.

Cook, N.J., Ciobanu, C.L., Wagner, T., and Stanley, C.J., 2007a, Minerals of the system Bi-Te-Se-S related to the tetradymite archetype: review of classification and compositional variation, Canadian Mineralogist, v. 45, pp. 665-708.

Cook, N.J., Ciobanu, C.L., Stanley, C.J., Paar, W., and Sundblad, K., 2007b, Compositional data for Bi-Pb tellurosulfides. Canadian Mineralogist, v. 45, pp. 417-435.

Cook, N.J., Ciobanu, C.L., and Howard, W.R., 2007c, Bi-tellurides in gold veins, BiTeKnoll (CLY prospect), southeastern British Columbia, Canada: Proceedings, Field workshop of IGCP-486, Espoo, Finland, August 26th-31st 2007. Geological Survey of Finland Opas, v. 53, pp. 31-37.

Cook, N.J., Ciobanu, C.L., and Danushevsky, L., 2007d, LA-ICP-MS determination of gold in Bi-minerals from deposits in the Fennoscandian Shield. Proceedings, Field workshop of IGCP-486, Espoo, Finland, August 26th – 31st 2007, Proceedings Volume: Geological Survey of Finland Opas v. 53, pp. 23-30.

Cook, N.J., Ciobanu, C.L., and Mao, J.W., 2009, Textural control on gold distribution in Au-free pyrite from the Dongping, Huangtuliang and Hougou gold deposits, North China Craton, (Hebei Province, China): Chemical Geology v. 264, pp. 101-121.

Coike, D.R., and McPhail, D.C., 2001, Epithermal Au-Ag-Telluride mineralization, Acupan, Baguio Philippines; numerical simulations of mineral deposition: Economic Geology, v. 96, pp. 109-131.

Djenchureva, R., 2006, Se-Te-bearing gold deposits of the Kyrgyz Tien Shan. In: Metallogeny of Precambrian Shields: Kyiv, Ukraine, September 2002. Abstract volume, pp. 49-53.

Douglas, N., Mavrogenes, J., Hack, A., and England, R., 2000, The liquid bismuth collector model: an alternative gold deposition mechanism: AGC Abstracts, v. 59, p. 135.
Törmänen, T.O., and Koski, R.A., 2005, Gold enrichment and the Bi-Au
Tarkian, M., Hünken, U., Tokmakchieva, M., and Bognanov, K., 2003,
Precious-metal distribution and fluid-inclusion petrography of the Elatise
porphyry copper deposit, Bulgaria: Mineralium Deposita, v. 38, pp. 261-
281.
Thomas, H.V., Patrck, R.A.D., and Gilmour, J.D., 2005, Progress in
developing Te–Xe dating of ore minerals, in: Mao, J.W. and Bierlein,
P.F. eds, Mineral Deposit Research: Meeting the Global Challenge:
Springer, Berlin-Heidelberg-New York, pp. 1427–1430.
Tombros, S., St. Seymour, K., and Spry, P.G., 2004, Description and conditions
of formation of new unnamed Ag–Cu and Ag–Cu–Au sulfotellurides in
epithermal polymetallic Ag–Te mineralization, Tinos Island, Hellas: 
Neues Jahrbuch für Mineralogie Abhandlungen, v. 179, pp. 295-310.
Tombros, S.F., St. Seymour, K., Zouzias, D., Mastrakas, N., Spry PG, and
Williams-Jones, A.E., 2007a, The evolution of an W-Ag-Au and
Ag-Au hydrothermal system, Tinos Island, Cyclades, Hellas (Greece), 
in: Andrew, C.J., ed., Mineral Exploration and Research: Digging Deeper:
Irish Association of Economic Geologists, Dublin, pp. 641-644.
Tombros, S.F., St. Seymour, K., Williams-Jones, A.E., and Spry PG, 2007b,
The genesis of epithermal Au-Ag mineralization, Panormos Bay,
Tinos Island, Cyclades, Greece: Economic Geology, v. 192, pp. 1269-
1294.
Tomkins, A.G., Pattison, D.R.M., and Frost, B.R., 2007, On the initiation of
metamorphic sulfide anatexis: Journal of Petrology, v. 48, pp. 1292-
1294.
Vikentyev, I., Seravkin, I., Moloshag, V., Skuratov, V., Yudovskaya, M., 
Vikentyev, I.V., 2006, Precious metal and telluride mineralogy of large
Cu-Au deposits: 12th Quadrennial IAGOD Symposium, Moscow, Extended abstract CD-ROM, abstract 327, 5 pp.
Zaykov, V., Novoselov, K., and Kotlyarov, V., 2006, Native gold and tellurides
in the Murugal and Çayeli volcanoclastic Cu deposits (Turkey): Proceedings,
Field Workshop of IGCP-486, 24-29 September 2006, Dokuzy Eylul University, Izmir, Turkey, pp. 167-172.
Zhao, Z.H., Zhang, P.H., Xiong, X.L., and Wang, Q., 2005, Au-Te deposits
and stable isotope studies of the Gies gold–silver telluride deposit, Judith
Mountains, Montana:. Economic Geology, v. 89, pp. 602–627.
Zhang, X., and Spry, P.G., 1994a, FO2PH: A Quickbasic program to calculate
mineral stabilities and sulfur isotopic contents in logFeO₂–pH space:
Mineralogy and Petrology, v. 50, pp. 287-291.
Zhang, X., and Spry, P.G., 1994b, Petrological, mineralogical, fluid inclusion,
and stable isotope studies of the Gies gold–silver telluride deposit, Judith
Mountains, Montana:. Economic Geology, v. 89, pp. 602–627.
Zoro, E., Servant, C., and Legendre, B., 2007, Thermodynamic assessment of the Ag–Au–Bi system: Calphad, v. 31, pp. 89-94.

Nigel J. Cook was born in London, England and received his degrees from the University of London: B.Sc. (Geochemistry) in 1982, Ph.D. (Ore Deposit Geology) in 1987. He recently moved to Adelaide, Australia, where he holds a position at the University of Adelaide jointly with the South Australian Museum. His research interests span a range of topics within ore deposit geology, sulphide geochemistry and mineralogy.

Cristiana L. Ciobanu was born in Bucharest, Romania, and received her Ph.D. in Ore Geology and Metallurgy from the University of Bucharest in 2000. She is currently a Research Associate at the University of Adelaide and South Australian Museum. Cristiana served as a Vice-Chairperson of IGCP project 486. Her research interests cover ore mineralogy and economic geology, with emphasis on tellurides and sulphosalts in gold deposits.