Compositional variation and distribution of Au-Ag-Hg and Au-Ag alloy in Nokomai and Nevis valley placers, New Zealand, and their implications for primary gold sources

JH Youngson[1], P Wopereis[2], LC Kerr[1,3] and D Craw[1]

[1] *Geology Department, University of Otago, PO Box 56, Dunedin, Email john.youngson@stonebow.otago.ac.nz*

[2] *L&M Mining, PO Box 13-442 Christchurch*

[3] *Present address: Striker Resources, Western Australia*

Abstract

Gold placers in the Nokomai and Nevis valleys are dominantly Quaternary in age. They occur mainly in western tributaries of the upper Nevis, eastern tributaries of the middle and upper Nokomai, and in the trunk valleys themselves. Placer gold in both valleys is dominantly α-phase Au-Ag-Hg alloy. Au-Ag alloy is absent or rare in most of the deposits, except in the lower Nokomai.

Alpha-Au-Ag-Hg alloy is typically coarse-grained (up to 2 cm), angular, and rarely flattened or folded. Crystalline texture, quartz intergrowths, and psuedo-hexagonal crystal-pluck cavities are common. Fluvial transport distance predicted from the maximum Flatness Index of Au-Ag-Hg alloy particles is typically less than 10-20 km. Coarse (up to 2 cm) cinnabar is commonly associated with the Au-Ag-Hg alloy, and both were probably derived from hydrothermal sources in western tributaries of the upper Nevis and eastern tributaries of the upper Nokomai. Minor secondary Au-Ag-Hg alloy occurs locally in the lower Nokomai, where it coats or cements detrital a-phase Au-Ag-Hg and Au-Ag alloy particles.

Au-Ag alloy dominates over Au-Ag-Hg alloy in the lower half of the lower Nokomai alluvial plain and in a raised channel incised into semischist basement adjacent to the plain. The Au-Ag alloy is rounded and commonly flattened and folded. Crystalline texture, quartz intergrowths, and pluck cavities are rare, and a fluvial transport distance of 25-40 km is estimated from maximum Flatness Index of Au-Ag alloy particles. The Au-Ag alloy, three types of garnet, magnetite, clinozoisite and well foliated schist boulders in the abandoned channel are not found in the pumpellyite-actinolite facies bedrock in the Nokomai. These components were derived from greenschist facies schist and sedimentary sources in Otago, many tens of kilometers north of the Nokomai catchment. They were transported to the Nokomai either in Wakatipu Glacier till or fluvio-glacial outwash that entered the valley via Nokomai Saddle, the confluence with the Mataura, or both.

Mercury-bearing minerals in hydrothermal systems in the Otago Schist appear to be restricted to the Caples Terrane, and either cinnabar or Au-Ag-Hg alloy, or both should be expected to occur in placer deposits derived from Caples Terrane rocks. A gold-mercury 'sub-paragenisis' is proposed for the Caples Terrane.

Introduction

Most of the placer gold in southern New Zealand was ultimately derived from mineralised quartz veins cross-cutting the Otago Schist (Figure 1) (Williams 1974a; Youngson & Craw 1996). This vein and placer gold is typically Au-Ag alloy, with Ag content less than 10%. Au-Ag-Hg alloys are rare, with only six southern South Island occurrences reported to date: five from fluvial placers in Otago (Hector & Skey 1866; Youngson & Craw 1995, 1996; Youngson 1996), and one from raised beach placers near the south coast (Mitchell 1996) (Figure 1).

Not all Au-Ag-Hg alloy found in sediments is hydrothermal in origin. Authigenic Au-Ag-Hg may form from reaction between detrital Au-Ag alloy and natural or anthropogenic

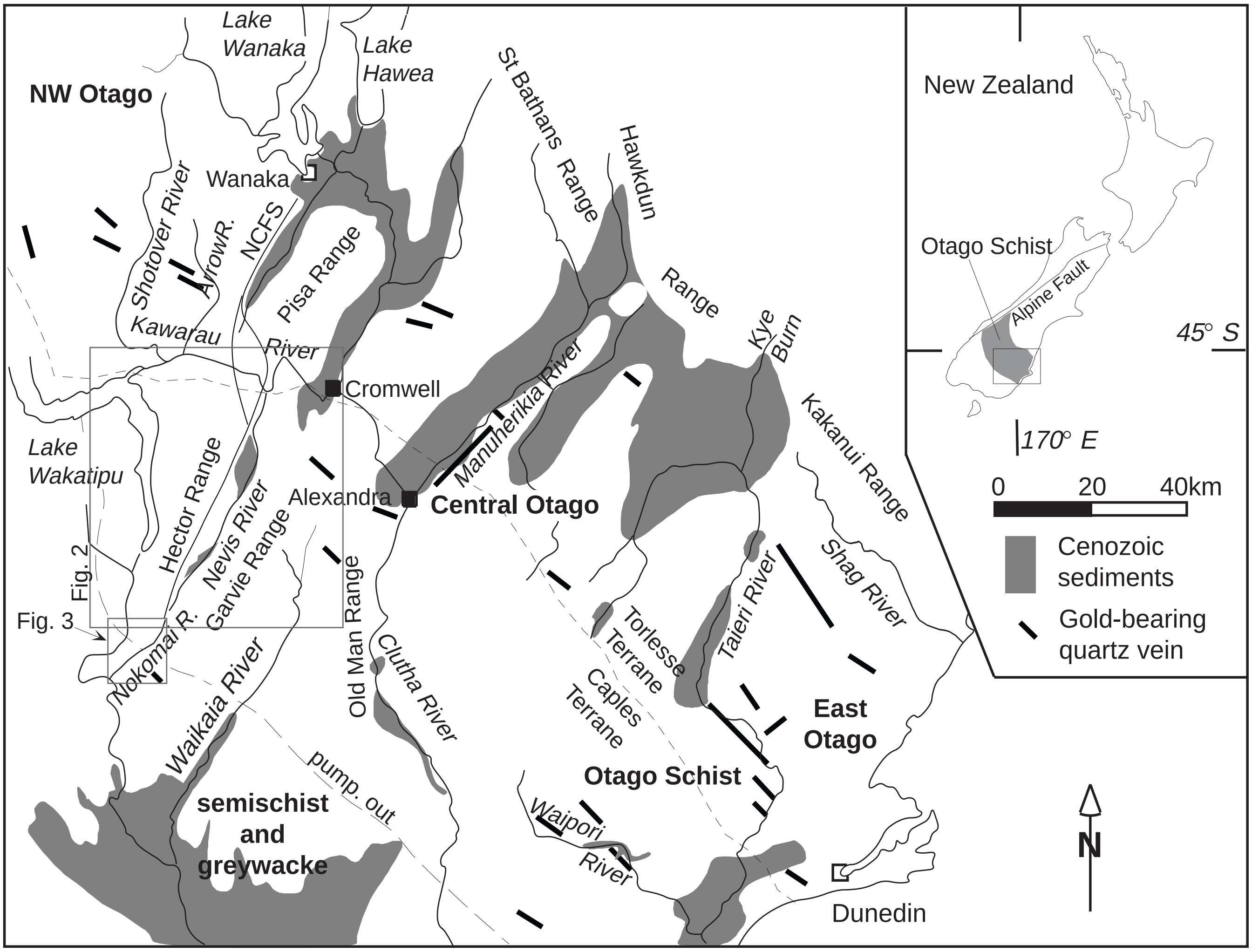

Figure 1. Location map showing geographic locations referred to in the text, gold-bearing quartz veins (after Williams 1974a), and Cenozoic cover rocks in Central Otago. NCFS is the Nevis-Cardrona Fault System. Approximate positions of the pumpellyite-out isograd (coarse dash), axis of the Otago Schist belt (uneven dash) (both after Mortimer, in press), the Caples Terrane–Torlesse Terrane boundary (fine dash; after Craw 1984 & Mortimer 1993), and Figures 2 & 3 are shown.

Hg. In addition, Au-Ag-Hg alloy, formed to improve commercial gold recovery, was sometimes lost to river systems during historic hard rock or alluvial mining operations (Black 1885; Harrison 1962; Youngson, in review). However, Au-Ag-Hg alloy of hydrothermal origin differs morphologically, compositionally and crystallographically from the secondary and artifact alloys (Youngson, in review; Youngson et al., in review); hence hydrothermal Au-Ag-Hg alloys are useful tracer minerals during exploration for source deposits.

In this study, the composition and distribution of Au-Ag-Hg and Au-Ag alloys in the Nokomai and Nevis valleys are used to constrain gold source areas, predict gold dispersal patterns, and explain the mixing of gold populations derived from different sources.

Terminology

An alloy is a mineral, or synthetic compound composed of two or more metallic elements. The term "amalgam" is commonly used for alloys of Hg with other metals (Berman & Harcourt 1938). It is non-specific and encompasses a range of synthetic and natural alloys of mercury with other metals. In this paper alloys of Hg with gold and silver are referred to as Au-Ag-Hg alloy. "Gold" is used as a collective term for Au-Ag alloy and Au-Ag-Hg alloy, regardless of composition. Alloy compositions given in the text are microprobe data in weight-percent.

For the purposes of this paper, hydrothermal Au-Ag-Hg alloys are taken as those precipitated from hydrothermal fluids. Secondary Au-Ag-Hg alloys are defined as those formed at low temperature (typically <50° C) in the near-surface environment by chemical reaction between detrital gold and natural or anthropogenically-introduced Hg. They are neither hydrothermal in origin nor formed intentionally to aid recovery of gold particles during gold-winning operations. The latter alloys are artifacts of recovery processes and are synthetic rather than secondary alloys (Youngson, in review).

Regional geology

Otago Schist basement in the study area formed during Mesozoic collision of volcanogenic (Caples Terrane) and quartzofeldspathic (Torlesse Terrane) greywacke suites. The schist belt grades from garnet-bearing greenschist facies rocks along its axis to Torlesse and Caples greywacke to the north and south, respectively (Figure 1) (Mortimer 1993). Numerous fault-hosted gold-quartz veins were formed during Cretaceous extension and unroofing of the schist, and Miocene extension related to the development of the Australia-Pacific plate boundary through New Zealand (Craw & Norris 1991) (Figure 1).

A regional low relief erosion surface was cut across basement terranes and local sedimentary basins during Cretaceous unroofing of the schist and Cretaceous-Oligocene regional marine transgression after Gondwana rifting (LeMasurier & Landis 1996). The unconformity and basal auriferous cover sediments are diachronous, ranging from Late Cretaceous in East Otago to early Miocene immediately east of the Nevis-Cardrona Fault System in Central Otago (Figure 1). The unconformity and auriferous cover strata are not preserved west of this fault system, where minor high land persisted during maximum transgression (Norris et al. 1978). Marine transgression from the south also occurred along an extensional Oligocene (Moonlight) aulacogen, which formed west of this high land immediately before development of the present Australia-Pacific plate boundary through New Zealand (Norris et al. 1978).

Most of the present relief and drainage has evolved since the Miocene, following inception of the plate boundary and related regional marine regression. Cover strata and the regional unconformity on basement have been locally eroded during uplift. In the Nevis valley, fine-grained Miocene fluvio-lacustrine strata (Manuherikia Group) locally overlie pumpellyite-actinolite and greenschist facies schist (Caples Terrane) east of the Nevis-Cardrona Fault System (Figures 1 and 2) (Williams 1974b; Douglas 1986). Most Manuherikia Group strata in the Nevis is either not gold bearing or only weakly auriferous. It is locally succeeded by Pliocene-Pleistocene Dell Sandstone and Schoolhouse Fanglomerate; the former recycled from the Miocene strata (Youngson et al. 1998), the latter auriferous immature schistose gravels derived from the adjacent ranges to the west (Williams 1974b).

There are no Manuherikia Group strata in the Nokomai, which is entrenched into pumpellyite-actinolite facies (Caples Terrane) semischist for most of its length. Quaternary alluvial fill in the Nokomai deepens from less than 10 m at Donkey Flat, to 24 m at the top end of a narrow alluvial plain in the lower 3-4 km of the valley (Figure 3), to 35 m at the bottom end of this plain. The alluvial fill consists of weakly auriferous (0-30 mg/m^3) schistose fluvial and intercalated fan gravels with 1-2 m of highly auriferous (1-3 g/m^3) bouldery lag gravels at their base. Carbon dating of peat overlying the basal lag gives an age of >45 ka. An undated, presumably Pleistocene, abandoned river channel is incised into schist along the northwestern margin of the lower Nokomai alluvial plain (Figure 3). Alluvial fill in this channel consists of brown, clay-cemented, weathered greywacke semischist and schist gravels and intercalated transverse bouldery fan gravels with a hard clay matrix. Coarse lag and debris flow deposits at the channel base have been extensively worked for gold. Terrace remnants of similar weathered gravels up to 120 m above the valley floor have also been worked for gold, especially on the northwestern side of the valley.

Cyclic climate variation and associated glaciations in the Pleistocene have played a major role in the geomorphic evolution of the Wakatipu region. Repeated glacial advances have periodically integrated catchments and resulted in complex drainage system changes and dispersal patterns for auriferous sediments. Distributary ice tongues and/or outwash sediments have pushed up several tributary valleys of the present Wakatipu, Kawarau and Mataura catchments and crossed low saddles into several adjacent catchments (Figure 1) (e.g. Brockie 1973; Turnbull & Forsyth 1988).

Sample locations

Nevis gold samples were recovered from alluvial gold mines in the lower reaches of Whittens and Drummond creeks, as well as from prospect pits at Sopers Flat and in Camerons, Swampy, Kingston, Tailrace, German, Little Stoney, and

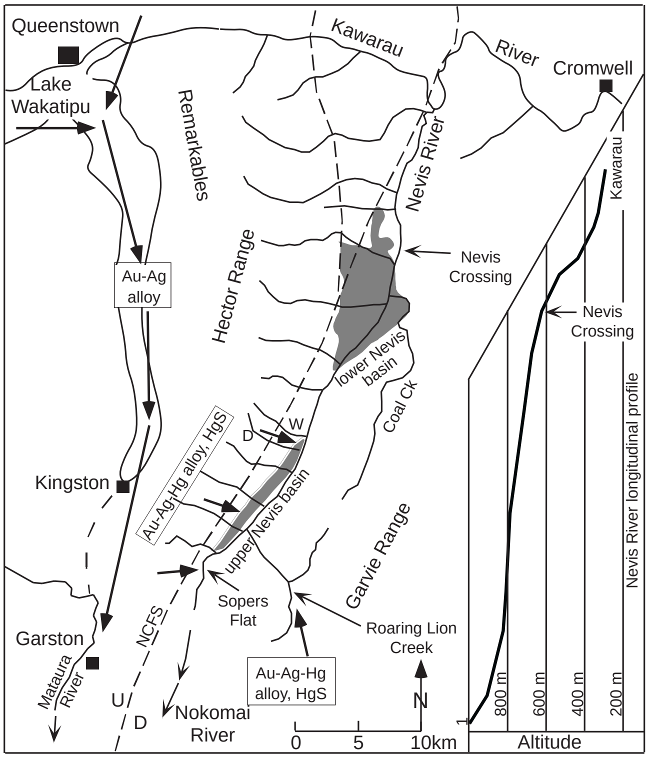

Figure 2. Detail map of the Nevis Valley. The western tributaries of the Nevis sampled for this study, not all of which are shown, lie between Sopers Flat and the northern end of the upper Nevis basin. Inset on right shows the longitudinal profile of the Nevis River. Shaded areas are Cenozoic cover rocks. NCFS is the Nevis-Cardrona Fault System. Inferred dispersal paths for HgS, Au-Ag and type 1 (α-phase) Au-Ag-Hg alloy are shown with coarse arrows. D = Drummond Creek, W = Whittens Creek.

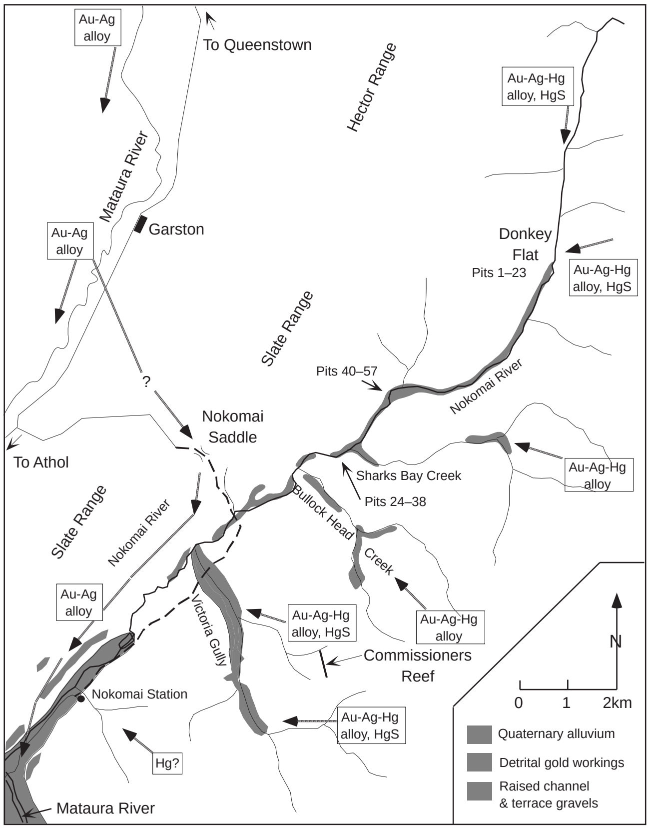

Figure 3. Map of the Nokomai valley showing the extent of historic alluvial gold workings and inferred dispersal paths for cinnabar, liquid Hg of possible hydrothermal origin, α-phase Au-Ag-Hg alloy, and Au-Ag alloy.

Stoney creeks. These tributaries all enter the Nevis from the west, between Sopers Flat and the downstream end of the upper Nevis Basin, and all samples were taken from downstream of the Nevis–Cardrona Fault System (Figure 2). Nokomai gold samples were recovered during mining of lag gravels at the base of alluvial flats in the lower Nokomai and an eastern tributary, Victoria Gully, a few kilometres upstream (Figure 3). Gold samples were also recovered from 57 prospect pits between Donkey Flat and Bullock Head Creek in the upper Nokomai, and from fossil channel gravels on the northwestern side of the lower Nokomai (Figure 3). Western tributaries of the Nokomai and all but one of the eastern tributaries of the Nevis contain no significant gold concentrations.

Gold characteristics

Gold composition

Hg content

Au-Ag-Hg alloy greatly dominates over rare (<1%) Au-Ag alloy in gold samples from the Nevis valley, and occurs without Au-Ag alloy in the upper Nokomai prospect pits, Victoria Gully mine, and upper end of the lower Nokomai valley alluvial plain (Table 1). Au-Ag-Hg alloy is less common in samples from the middle reaches of this alluvial plain (<50%), and is absent in its lower reaches. Au-Ag-Hg alloy is rare in the abandoned channel gravel on the northwestern side of the lower valley, the gold in which is dominantly Au-Ag alloy (Table 1).

The Au-Ag-Hg alloy in the Nevis and Nokomai typically contains between 0.3% and 11% Hg (type 1). However, Au-Ag-Hg alloy with 20–37% Hg (type 2) was locally abundant where a tributary stream (fan) enters the lower Nokomai alluvial plain from the southeast (Figure 3), and also present as rare particles in two other Nokomai samples (Table 1). During a recent mining operation, nearly all of the gold recovered from basal lag gravel at the mouth of this tributary (type 1 Au-Ag-Hg alloy plus minor Au-Ag alloy) was coated with type 2 Au-Ag-Hg alloy. Drops of liquid Hg were also present in this gravel. The type 2 Au-Ag-Hg alloy occurs as unzoned overgrowths on Au-Ag and type 1 Au-Ag-Hg alloys and, rarely, as zoned overgrowths. The unzoned overgrowths contain 20–37% Hg, whereas zoned overgrowths have an Hg-rich (20-37%) inner zone overlying the host particle, and a relatively Hg-poor (12%) outer zone (Figure 4). Microprobe analyses of type 1 and type 2 Au-Ag-Hg alloys from the Nevis and Nokomai are plotted on an Au-Ag-Hg ternary in Figure 5.

Ag content

The Ag content of Au-Ag alloy and both types of Au-Ag-Hg alloy in the Nevis and Nokomai valleys is typically less than 8%, although a few particles from the Nokomai contain up to 13% (Figure 5). The Ag content of unzoned Hg-rich type 2 Au-Ag-Hg alloy is consistently lower than that of the type 1

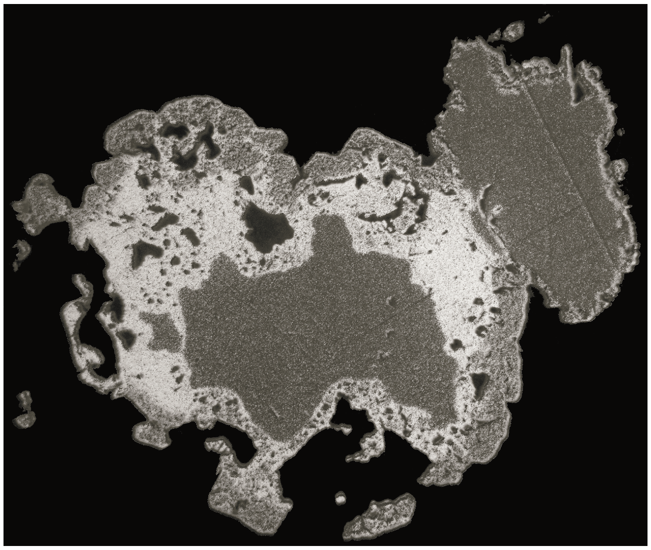

Figure 4. Polished section (reflected light) through detrital zoned Au-Ag-Hg alloy (left) and un-zoned type 1 (α-phase) Au-Ag-Hg alloy (right) from lower Nokomai valley, which have been cemented to form a composite particle. The dark gray inner of the zoned particle is the remnant core of a detrital type 1 (α-phase) Au-Ag-Hg alloy particle. The white central zone is Hg-rich (35% Hg) secondary Au-Ag-Hg alloy, and the outer dark gray zone is secondary Au-Ag-Hg alloy that has been partly leached of Hg (12% Hg). A thin rim of partly leached secondary Au-Ag-Hg alloy is also locally present on the un-zoned particle. The composite particle is 1.4 mm across.

NEVIS	Gold alloy subtype(s)	Maximum size (mm)	Roundness range	Particle flattening	Particle folding	Crystalline texture	Intergrowths or pluck cavities	Maximum Flatness Index [FI=(a+b)/2c]	Fluvial transport distance estimate
Soper's Flat	α-phase Au-Ag-Hg rare Au-Ag	5	va-sa (rare r)	rare	rare	common	abundant	12	<10-15 km
Little Stoney Ck.	α-phase Au-Ag-Hg	2	va-r	rare	absent	common	common	14 21	<10-15 km some 30 km
Stoney&German Creeks	α-phase Au-Ag-Hg rare Au-Ag	3	va-sa (rare r)	rare	absent	rare	abundant	11	<10-15 km
Tailrace Creek	α-phase Au-Ag-Hg rare Au-Ag	4	a-r	rare	rare	rare	common-abundant	13 19	10-20 km some 20-30 km
Kingston Creek	α-phase Au-Ag-Hg	3	va-a	absent	absent	rare	abundant	9	<10 km
Swampy Creek	α-phase Au-Ag-Hg rare Au-Ag	4	va-sa	absent	absent	common	abundant	9	<10 km
Drummond Creek	α-phase Au-Ag-Hg rare Au-Ag	4	a-r	rare	rare	rare	common	14 18	10-20 km some 20-30 km
Camerons Creek	α-phase Au-Ag-Hg	6	a-sr	rare	absent	rare	moderately common	13	10-20 km
Whittens Creek	α-phase Au-Ag-Hg rare Au-Ag	7	va-sa	rare	absent	rare	abundant	10 17	<10 km some 20-30 km
NOKOMAI									
Donkey Flat	α-phase Au-Ag-Hg	5	va-sa (rare sr)	absent	absent	abundant	abundant	11	<10-15 km
Donkey Flat to Sharks Bay Ck.	α-phase Au-Ag-Hg rare hex. Au-Ag-Hg	5	va-sa	absent	absent	abundant	abundant	9	<10-15km
Sharks Bay Ck. to Bullock Head Ck.	α-phase Au-Ag-Hg	4	va-r	absent	absent	abundant	abundant	12	<10-20 km
Victoria Gully mine	α-phase Au-Ag-Hg rare hex. Au-Ag-Hg	20	va-sa (rare sr)	absent	absent	abundant	abundant	8	<10 km
Nokomai flats (top end)	α-phase Au-Ag-Hg	8	sa-sr	rare	rare	common	common	15	15-25 km
Nokomai flats (central portion)	α-phase Au-Ag-Hg Au-Ag	5	sa-wr	common	some	some	some	14 24	15-25 km 25-40 km
Nokomai flats (bottom end)	Au-Ag	7	sr-wr	common	rare	rare	rare	22	25-40 km
Lower Nokomai fossil channel	Au-Ag rare α-phase Au-Ag-Hg	6	sa-wr	common	common	rare	rare	21 15	25-40 km 15-25 km

Table 1. Summary data for the morphological characteristics and transport distance estimates for the gold alloy sub-types in Nevis and Nokomai valley placer deposits.

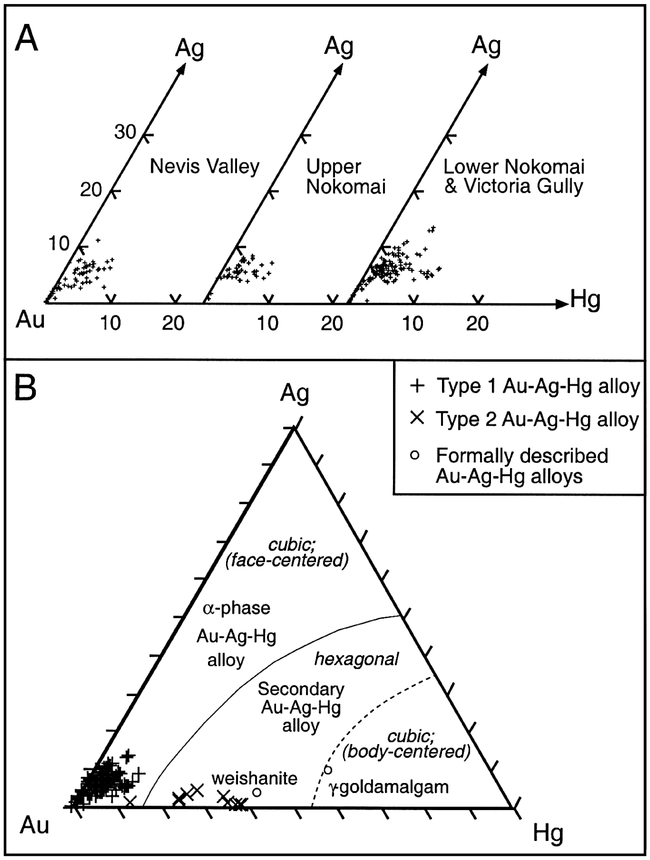

Figure 5. (A) Au-Ag-Hg ternary plots showing compositional variation of type 1 Au-Ag-Hg alloy from the Nevis, Upper Nokomai, and lower Nokomai and Victoria Gully. (B) Au-Ag-Hg ternary comparing the composition of type 1 Au-Ag-Hg alloy from the Nevis (n=52) and Nokomai (n=121) valleys with type 2 Au-Ag-Hg alloy from the Nokomai (n=10). Internal field boundaries are from Youngson (in review), and that for hydrothermal α-phase Au-Ag-Hg alloys is drawn for a temperature of 25°C.

Au-Ag-Hg or Au-Ag alloy particles that host them. In zoned type 2 alloys, the Ag content of the inner zone is consistently lower than that in both the host particle and the outer zone of the type 2 alloy.

Particle rims

Thin (<10μm) Hg±Ag-depleted rims occur on many type 1 Au-Ag-Hg alloys and zoned or unzoned type 2 alloys. However, no leached rims are present on those parts of type 1 alloy that are overgrown with type 2 alloy. Rim zonation is consistent with Ag- and Hg-leaching from particle surfaces, with relatively greater leaching of Hg due to its higher solubility (Hem 1970).

Gold morphology and colour

Type 1 Au-Ag-Hg alloy

Type 1 Au-Ag-Hg alloy has the same colour and texture as Au-Ag alloy with similar fineness and transport history, and can only be identified by chemical analysis (Youngson submitted). Both are typically bright yellow in polished section but paler with increasing Ag content.

Crystalline textures are uncommon in the type 1 Au-Ag-Hg alloy in gold samples from the Nevis valley, but quartz intergrowths and hexagonal pluck cavities are abundant (Table 1). Flattened and folded particles are rare and not present in several samples. Very angular, angular, and sub-angular particles predominate. A small proportion (<10%) of some of the Nevis samples is much more rounded, and some of these particles have been folded and/or flattened as well. This morphologically contrasting proportion is independent of gold composition, however, and applies to type 1 Au-Ag-Hg and Au-Ag (below) particles.

Crystalline textures, quartz intergrowths and hexagonal pluck cavities are common in type 1 Au-Ag-Hg alloy from the upper Nokomai pits, Victoria Gully and the lower Nokomai alluvial plain (Table 1). Particle flattening and/or folding is absent or rare in all of these samples. Most particles are very angular, angular, or sub-angular, and exhibit only minor rounding.

Type 2 Au-Ag-Hg alloy

The morphology of the Hg-rich, type 2 Au-Ag-Hg alloy differs substantially from that of type 1 Au-Ag-Hg alloy and is described fully by Youngson et al. (in review). Type 2 alloy occurs as variable thickness (up to 200μm) overgrowths that coat or cement type 1 alloy or, rarely, Au-Ag alloy, host particles (Figure 6). Nearly all of the host particles have been partly rounded before addition of the type 2 alloy, reflecting transport of the host before addition of the type 2 alloy. These relationships clearly indicate a two-stage origin for particles coated or cemented with type 2 Au-Ag-Hg alloy.

Type 2 alloy is composed of masses of porous, poorly developed hexagonal crystals, commonly separated by narrow crevasse-like cavities around their margins, filiform-textured

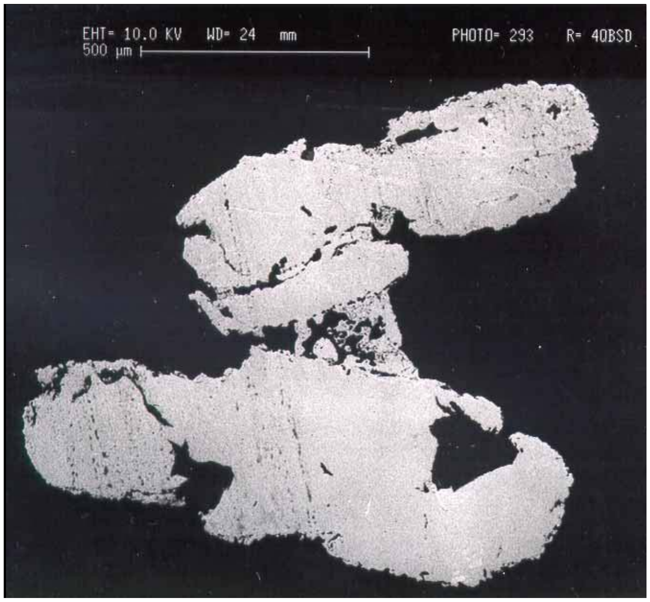

Figure 6. Scanning electron microscope image of two rounded particles of type 1 (α-phase) Au-Ag-Hg alloy which have been cemented together by highly porous type 2 (secondary) Au-Ag-Hg alloy. The top particle is 0.8 mm long.

alloy, globular anhedral alloy, or combinations of these (Youngson, in review; Youngson et al. in review). Unzoned type 2 alloy and the inner zone of zoned type 2 alloy are both silver-grey in colour, white in polished section, and perforated by numerous 1-15 μm pores. The outer zone of zoned type 2 alloy is a brassy-gold colour, pale yellow in polished section, and perforated by abundant small pores (Figure 4). The pores observed in type 2 Au-Ag-Hg alloy are rare or absent in type 1 alloy.

Au-Ag alloy

The morphology of the Au-Ag alloy that dominates gold samples from the lower half of the lower Nokomai alluvial plain and the adjacent abandoned channel contrasts strongly with the morphology of type 1 Au-Ag-Hg alloy from the same samples and elsewhere in the Nokomai. Crystalline textures are rare in the Au-Ag alloy, intergrowths and pluck cavities are uncommon, and rounded particles dominate over angular particles. Up to 50% of the particles have been flattened and folding is common (Table 1). Although the relative proportion of rounded, flattened and folded gold generally increases downstream through the lower Nokomai alluvial plain, this change is dependent on composition and corresponds to an increase in the relative proportion of Au-Ag to Au-Ag-Hg alloys in the samples. Considered individually, there is no significant change in the morphology of either Au-Ag alloy or type 1 Au-Ag-Hg alloy downstream through the lower Nokomai alluvial plain (Table 1).

The small quantity (<1%) of Au-Ag alloy particles present in several Nevis samples (Table 1) have a similar range of morphological variation to that observed in type 1 Au-Ag-Hg alloy particles in the same and nearby samples. However, a small proportion (<10%) of more rounded, more flattened, and folded gold in some of the Nevis samples is independent of composition and includes both Au-Ag-Hg and Au-Ag alloy particles.

Associated rock clasts and heavy minerals

Rock clasts

Rock clasts associated with the Au-Ag alloy in the abandoned channel in the lower Nokomai are pervasively weathered, but preserved metamorphic fabric in many clasts is consistent with derivation from pumpellyite-actinolite semischist basement within the catchment (Table 2). Boulders up to 0.5 m across of well-foliated, probably greenschist facies schist are common in the basal lag, and rare scarlet-coloured jasperlitic chert cobbles are present in terrace gravels and mine tailings up to 120 m above the abandoned channel.

Mineral	Nokomai bedrock	Nevis bedrock	Upper alluvial plain	Abandoned channel	Mid-lower alluvial
epidote	common (d)	rare (cores to clinozoisite)	common	common	common
clinozoisite	rare/absent (h)	present/common	rare	common	moderate
hematite	common	present	common	moderate	moderate
magnetite (Ti-poor)	-rare/absent	Generally rare, common near Kawarau R.	rare	common	moderate
garnet					
Fe-Mn	? (d)	? (d)	-	rare	-
Fe-Mg			-		-
Fe-Mg-Ca			-		-
pyrite	rare	rare	abundant (a+d)	rare (d)	common (a+d)
arsenopyrite	rare	rare	rare	-	rare
cinnabar	none known	small veins	common up to 1cm	rare	common sand size
Mercury	none known	none known	-	present	-
α-phase Au-Ag-Hg alloy	Victoria Gully ?	none known	common	rare	rare/absent
Secondary Au-Ag-Hg alloy	none known	none known	-	-	common
Au-Ag alloy	Victoria Gully ?	-	-	common	common

Table 2. Summary of heavy minerals in Nokomai and Nevis valley bedrock and placers. (d) = detrital, (h) = hydrothermal, (a) = authigenic.

Epidote and clinozoisite

Most of the heavy minerals in the alluvial plain and abandoned channel in the lower Nokomai are consistent with derivation from pumpellyite-actinolite facies semischist basement within the catchment. However, abundant clinozoisite with first order interference tint in gravels of the abandoned channel and lower half of the alluvial plain is not found in bedrock of the Nokomai catchment (Table 2). Rare euhedral clinozoisite occurs in a hydrothermal quartz vein in Victoria Gully (Figure 3) but, in contrast with the detrital clinozoisite, has anomalous blue interference tint. Clinozoisite with first order interference tint is common in greenschist facies rocks to the north, closer to the axis of the schist belt (Bishop 1972; Cooper 1972), including those in the Nevis valley. Some of the Nevis clinozoisite contains relict cores of epidote, which is common as discrete grains in the lower rank Nokomai schist.

Magnetite

Coarse (up to 4 mm) magnetite containing little or no titanium is common in the abandoned channel and lower half of the alluvial plain in the lower Nokomai, but is rare in Nokomai, upper Nevis and middle Nevis bedrock (Table 2). It is locally abundant in metavolcanic horizons in greenschist facies schist in the lower Nevis, especially near and northwest of its confluence with the Kawarau (Figure 1) (Craw 1984). Coarse detrital magnetite is also abundant in the Mataura valley to the west, particularly in fluvial outwash sediments derived from Pleistocene Wakatipu glaciers, and in the Kawarau valley and its northern tributaries (Figure 1).

Garnet

Rare garnets are present in the abandoned channel in the lower Nokomai, but were not found in the Nokomai itself, and do not occur in either Nokomai or Nevis valley bedrock (Table 2). Microprobe analyses recast to the Almandine–Spessartine–Grossular ternary system indicate three compositionally distinct garnet types (Figure 7). All three types contain less than 1.5 wt.% MgO. Comparison with garnets from potential source rocks recast to the same ternary system (Figure 7) suggests that greenschist and amphibolite facies schists in northwest Otago (White 1996, Mortimer, in press) are possible sources for both the type 1 and type 2 garnets. Some of the the type 2 garnets overlap with those from Western Fiordland Orthogneiss, but the latter contain substantially more MgO (up to 11 wt.%; Bradshaw 1989) than type 2 garnets from the Nokomai. Stewart Island intrusives (Frewin 1987, Peden 1988) appear the most likely sources for the type 3 Nokomai garnets.

Cinnabar

Coarse (up to 1 cm), commonly crystalline, and fine-grained detrital cinnabar is abundant in the Nokomai upstream from Sharks Bay Creek, in Victoria Gully, and at the upper end of the lower Nokomai alluvial plain (Table 2). Abundance and grain size decrease downstream through the alluvial plain, with the cinnabar rarely being larger than fine sand (0.25 mm) in the lower reaches of the plain. Coarse, crystalline cinnabar is also abundant at Sopers Flat, and in western tributaries of the Nevis upstream from German Creek (Figure 2, Table 2). It is either rare or present in small quantities only in Nokomai prospect pits downstream from Sharks Bay Creek, and in samples from Nevis tributaries downstream from German Creek. Cinnabar is absent or rare in samples from the abandoned channel gravels in the lower Nokomai. A previously undocumented cinnabar-bearing vein on the slopes of the Hector Range west of Sopers Flat (Soper brothers, pers. comm. to P.W., 1996) (Figure 2) could be a source for some detrital cinnabar in the Nevis, but no cinnabar-bearing veins are known to exist in the Nokomai catchment.

Rare hydrothermal cinnabar deposits are reported from elsewhere in the Otago Schist (Hutton & Ulrich 1875; Williams 1974a), one of which lies about 30 km southeast of the Nokomai in the Waikaka valley (Figure 1) (Henderson 1923). Detrital, commonly coarse, cinnabar occurs in close proximity to each of these sources (Morgan, 1914; Marshall 1918; Healy 1936; Williams 1974a). Cinnabar is brittle and rapidly comminuted in fluvial systems, however, and grain size decreases rapidly downstream from each source. Thus, coarse-grained cinnabar in the upper Nokomai, Victoria Gully, lower Nokomai, and Nevis, and rapid decrease in abundance and grain size downstream from each locality, imply derivation from a number of local sources rather than widespread dispersal from a single source. The rarity of the cinnabar in the abandoned channel gravel (Table 2) may indicate an external source for this gravel, but could alternatively result from cinnabar sources within the catchment not being exposed or eroded at the time of gravel deposition in the abandoned channel.

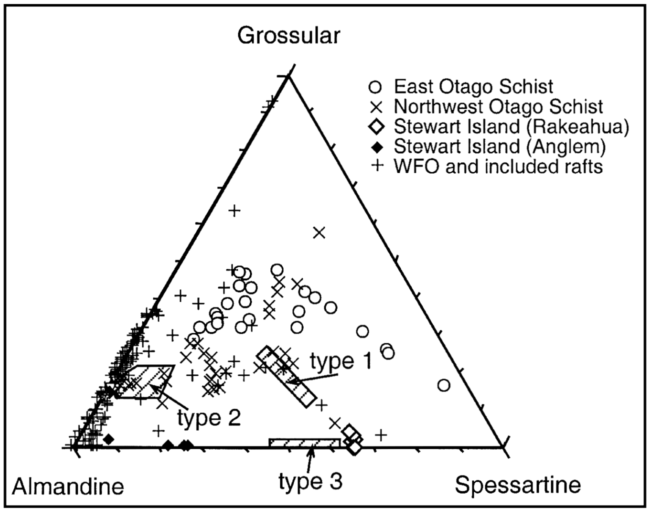

Figure 7. Compositional range of the three types detrital garnet from the lower Nokomai valley recast to the Almandine–Spessartine–Grossular system. Compositional variation of garnets from the Western Fiordland Orthogneiss (WFO) (Bradshaw 1989), Anglem Complex (Frewin 1987), Rakeahua Batholith, (Peden 1988), Otago and Alpine schists in northwest Otago (Cooper 1970, White 1996), and Otago Schist in East Otago (Brown 1965, 1967), are shown for comparison. Potential sources for the Nokomai detrital garnets are discussed in the text.

Discussion

Gold alloy subtypes

Au-Ag alloy

Although type 1 Au-Ag-Hg alloy dominates most of the Nokomai and Nevis gold samples, Au-Ag alloy was detected locally by routine microprobe analysis of samples (Table 1). Significant morphological differences between Au-Ag and type 1 Au-Ag-Hg alloy subtypes were noted only in samples from the abandoned channel and lower reaches of the lower Nokomai alluvial plain, where Au-Ag alloy is more rounded and more flattened than Au-Ag-Hg alloy in the same or nearby samples (Table 1).

Au-Ag-Hg alloys

Au-Ag-Hg alloys of hydrothermal and secondary origin differ in composition, crystal structure, colour and morphology (Youngson, in review). With two rare exceptions (weishanite and γ-goldamalgam), all hydrothermal Au-Ag-Hg alloys have face-centered cubic structure and plot within the α-phase field in the Au-Ag-Hg ternary (Figure 5B) (Basu et al. 1981; Healy & Petruk 1990; Youngson, in review). Conversely, secondary Au-Ag-Hg alloys formed by reaction between gold and liquid Hg in the near-surface environment are more mercury-rich than α-phase Au-Ag-Hg alloy of hydrothermal origin, and have hexagonal structure (Figure 5) (Youngson, in review).

Type 1 Au-Ag-Hg alloy from the Nevis and Nokomai valleys plot within the α-phase field in the Au-Ag-Hg ternary (Figure 5B), have cubic structure (Youngson, in review), and exhibit morphological and textural features indicative of near-source detrital gold (Table 1). Consequently, they are interpreted to be detrital α-phase Au-Ag-Hg alloys of hydrothermal origin.

Type 2 Au-Ag-Hg alloys that coat or cement gold locally in the Nokomai are hexagonal (Youngson, in review), exhibit textural relationships indicative of a two-stage origin (Figures 4 and 7), and all but two analyses plot outside the α-phase field (Figure 5). These latter two analyses are from the outer zone of zoned type 2 alloys and plot within the α-phase field. In both cases the outer zone is brass-gold in colour and highly porous, features interpreted by Youngson (in review) and Youngson et al. (in review) to reflect leaching of Hg from the outer several tens of microns of particles. Consequently, type 2 Au-Ag-Hg alloy in the Nokomai is interpreted to be secondary, and formed after some fluvial transport of the Au-Ag and α-phase Au-Ag-Hg alloy hosts. Compositionally and morphologically similar secondary Au-Ag-Hg alloy is common in river systems elsewhere that have been contaminated with liquid mercury (Atanasov & Jordanov 1983; Atanasov et al. 1988; Youngson 1996; Youngson, in review).

Gold sources

α-phase Au-Ag-Hg alloy

Crystalline habit, abundant quartz intergrowths and pluck cavities, and minimal rounding and flattening of the detrital α-phase Au-Ag-Hg alloy in the Nokomai valley samples (Table 1) strongly suggest local primary sources for this gold. Moreover, gold distribution and the morphological similarity between all Nokomai samples upstream of the alluvial plain in the lower valley (Table 1) imply that the gold sources are, or were, in several eastern tributaries in the upper half of the catchment (Figure 3). One such vein in Victoria Gully (Figure 3) was worked historically, but the composition of that gold is unknown and none was found during this study. A soil-sampling program throughout the Nokomai catchment (by L&M Mining) in the 1990s did not locate significant gold anomalies (Kerr & Wopereis 1996).

Abundant gold-quartz intergrowths and pluck cavities in nearly all of the α-phase Au-Ag-Hg alloy from the Nevis, and minimal rounding and flattening of the majority of particles (Table 1), imply local primary sources for most of that gold as well. The abundance of gold in all of the western tributaries sampled, and virtual absence of gold in all but one of the eastern tributaries, implies that the primary sources are, or were, within the western tributaries of the Nevis. Morphological similarity between samples from all of these tributaries (Table 1) precludes more than a few kilometres of transport parallel to the Nevis valley axis. However, the small proportion of more deformed Au-Ag-Hg and Au-Ag alloys in some Nevis samples suggests either more distant primary sources for that gold or minor recycling from pre-existing placers, possibly the Miocene-Pliocene sedimentary strata within the valley. The distribution of α-phase Au-Ag-Hg alloy in the Nevis and Nokomai valleys (Figures 2 and 3) would support either small primary sources within individual tributaries, or larger primary sources trending sub-parallel to the valley axes.

Au-Ag alloy

Similarity in the range of morphological variation within the Au-Ag and Au-Ag-Hg alloy sub-types in individual Nevis samples implies similar transport and deformation histories for each sub-type. The small proportion (<10%) in some samples, of significantly more deformed particles of both sub-types suggests that some particles of each sub-type have a relatively longer transport history. Again, this could be due to more distant primary sources or result from recycling of gold from auriferous Miocene-Pliocene strata within the valley.

The dominance of Au-Ag alloy over α-phase Au-Ag-Hg alloy in the lower half of the lower Nokomai alluvial plain and the gravel in the adjacent abandoned channel contrasts strongly with all other Nokomai and Nevis samples (Table 1), in which α-phase Au-Ag-Hg alloy dominates. The Au-Ag alloy in the lower Nokomai is much more deformed than α-phase Au-Ag-Hg alloy in the same or nearby samples. As both alloys have similar Mohs hardness (2–3), morphological differences between them in the lower Nokomai could reflect recycling of the Au-Ag alloy from older sediments no longer preserved in the Nokomai and/or relatively more distant primary sources for the Au-Ag alloy.

Transport distance estimates

Rounding, flattening and folding of detrital gold preserves a cumulative record of the deformation it undergoes during transport from a primary source to the ultimate site of deposition. Particle flattening is particularly important, because it progressively lowers the surface area-to-volume ratio of gold which, in turn, enhances the entrainability of particles in a given current. On-going flattening thus allows gold particles to be progressively transported to lower-energy parts of the fluvial system (Youngson & Craw 1999). Consequently, there is a predictable relationship between the maximum flatness of gold particles and maximum transport distance in gravel bed-load rivers. This has been quantified for the Arrow-Kawarau-Clutha River system in Otago, where the gold sources are well-constrained (Youngson 1998; Youngson & Craw 1999), and similar relationships have been established elsewhere (Hérail et al. 1990, Knight et al. 1994). Fluvial transport distance estimates for Nevis and Nokomai gold (Table 1) were made using the method of Youngson & Craw (1999). This method relates fluvial transport distance to the maximum flatness index for gold particles in a particular sample [F.I.=(a+b)/2c, where a, b, and c are the mutually perpendicular long, intermediate and short axes of the particle]. The method cannot account for any glacial transport, however, as little or no flattening of gold occurs during such transport.

The small proportion of relatively more deformed gold particles in some Nevis samples has higher maximum flatness index (18–25) than that for the bulk of the gold (<15) in those samples (Table 1). Maximum transport distance estimates of 20–30 km for the more flattened gold is consistently greater than the <10–20 km estimates for the bulk of the Nevis gold (Table 1), and supports more distant primary sources and/or a recycling history for the more deformed gold. Conversely, the shorter transport distance estimates for the bulk of the Nevis gold are compatible with our inference of primary sources within the western tributaries of the Nevis. Similarly, low maximum flatness index (<15) and short (<10–20 km) maximum transport distance estimates for a-phase Au-Ag-Hg alloy in all samples upstream of the alluvial plain in the lower Nokomai (Table 1) support our inference of primary sources in the upper eastern tributaries of the Nokomai. Furthermore, 15–25 km estimates for α-phase Au-Ag-Hg alloy within the alluvial plain are also consistent with derivation from such sources.

The 25–40 km fluvial transport estimates for Au-Ag alloy in the abandoned channel and alluvial plain in the lower Nokomai are enigmatic, firstly because the Nokomai valley is only about 20 km in length (Figure 3), and secondly because detrital Au-Ag alloy has not been found elsewhere within the catchment. The fluvial transport distance estimates require either considerable fluvial recycling of Au-Ag alloy within the Nokomai, or a former connection with an Au-Ag alloy source outside the present Nokomai catchment. The absence of Au-Ag alloy elsewhere in the Nokomai does not support the possibility of local Au-Ag sources or recycling within the catchment.

Associated provenance indicators

Rock clasts, magnetite and clinozoisite

Boulders of well-foliated schist, abundant clinozoisite, and coarse magnetite associated with Au-Ag alloy in the lower Nokomai require sources in higher grade, probably greenschist facies, rocks than the pumpellyite-actinolite facies semischist within the catchment. Hematite is the dominant iron oxide in the Nokomai bedrock, but this has recrystallised to magnetite in greenschist facies rocks farther north (e.g. Craw 1984). Clinozoisite is an index mineral for the greenschist facies, hence the nearest source rocks for the magnetite and clinozoisite in the lower Nokomai are the greenschist facies rocks many tens of kilometers north of the Nokomai catchment (Figure 1). The source of allochthonous scarlet-coloured jasperlitic chert cobbles in high terrace gravels and mine tailings above the lower Nokomai alluvial plain is unknown, but similar rocks are common in Caples Terrane greywacke basement west of Lake Wakatipu, and in fluvial or fluvio-glacial outwash derived from that area (Turnbull 1980, 1988).

Garnets

The three compositionally distinct garnets types in the abandoned channel in the lower Nokomai demand a complex transport history to concentrate them together if they are derived from the northwest Otago schists (types 1 & 2 garnet) and Stewart Island (type 3 garnet) intrusive source rocks inferred from Figure 7. Northward marine currents and longshore drift since at least the Paleocene are indicated by garnets and other heavy minerals derived from south coast, and/or Fiordland intrusives in early- to mid-Tertiary marine sandstones throughout Otago (Hutton & Turner 1936; Sharp 1993). Garnets with the same composition as type 3 garnets in the Nokomai occur 50 km southeast of the Nokomai in Quaternary sediments containing detritus recycled from marine strata (Falconer 1987). Both occurrences probably reflect widespread dispersal during Tertiary marine transgression. If the type 1 and type 2 Nokomai garnets are derived from northwest Otago schists, then alternate transport mechanisms are required to get them into the Nokomai, as those source rocks were not exhumed until after the marine transgression (Adams 1981; Sutherland 1996).

Although marine transgression could account for widespread occurrence of type 3 garnets in Central Otago, the absence of all three garnet types anywhere in the Nokomai other than in the abandoned channel does not favour transgression for getting the garnets into the Nokomai itself. The most likely source rocks for types 1 & 2 garnet (northwest Otago schists), and Tertiary marine sediments (Turnbull et al. 1975), which are a potential intermediate source for the type 3 garnets, lie many tens of kilometres north of the Nokomai catchment. Southward sediment transport required to get garnets from these rocks into the Nokomai is supported by the magnetite, clinozoisite and greenschist facies rock clasts associated with garnets in the abandoned channel gravel. Furthermore, Au-Ag alloy in the abandoned channel and lower half of the Nokomai alluvial plain is a common hydrothermal vein mineral in the greenschist facies schist to the north as well (Figure 1) (Williams 1974a; Craw & Norris 1991). Thus, it is possible that the Au-Ag alloy, garnets, magnetite, clinozoisite and greenschist facies boulders in the lower Nokomai were all derived from basement rocks and intermediate sedimentary sources north of the Nokomai catchment. Dispersal mechanisms from these sources are discussed below.

Alternate dispersal mechanisms

River capture and tectonic slope reversal

The longitudinal profile of the Nevis River is concave in its upper and lower reaches, but convex in the middle reaches (Figure 2). This profile is atypical compared to other Kawarau tributaries such as the Arrow and Shotover, which are concave throughout (Youngson & Craw 1999). We suggest that convexity of the Nevis profile reflects capture of the headwaters of an ancestral Nokomai River by a former steep short tributary of the Kawarau (Figures 1 and 2). Further, that capture occurred at a former drainage divide in the vicinity of Nevis crossing (Figure 2), and that the middle and upper reaches of the present Nevis represent the former upper and middle reaches, respectively, of the ancestral Nokomai. These reaches are part of a broad low-relief upland plateau that extends over 25 km eastward from the Nevis to the Clutha valley (Stirling 1990) (Figures 1 and 3). The plateau itself has been locally warped by Quaternary growth of schist antiforms (Stirling 1990). With the exception of the Nevis area, the upland is drained to the south by rivers with low gradients in their upper reaches on the upland (Figure 1). The portion of the upland inferred to have formerly drained southward by the ancestral Nokomai has been tectonically tilted by uplift along a complex zone of active faults and antiforms that flank the Nevis valley. These structures converge toward the low saddle between the Nevis and the Nokomai (Beanland & Barrow-Hurlbert 1988; Kerr et al., in press). The Nevis portion of the upland is now drained northward to the capture point by the middle and upper reaches of the Nevis, and ultimately to the Kawarau (Figures 1 and 3). Presumably, a low stream gradient in the upper reaches of the ancestral Nokomai on the plateau was insufficient to maintain an antecedent southward course through the zone of uplift.

Prolonged low relief on the plateau is indicated by up to 300 m of sandy sediments and oil shale in Miocene strata in the Nevis, with coarse detritus and significant amounts of gold first appearing in Pliocene and Pleistocene transverse fan sediments derived from the west (Williams 1974b, Douglas 1986). Greenschist facies clasts and clinozoisite are common in the fan sediments but magnetite and garnet are not. Although some of the allochthonous clasts and minerals in the lower Nokomai could have been transported from these fan sediments by an ancestral Nokomai, we suggest that its gradient on the upland plateau was probably insufficient to transport gold or coarse clasts of schist to the south. This contention is supported by the absence in all Nokomai samples upstream of the Nokomai alluvial plain, of greenschist facies detritus and the relatively more deformed gold that is present in most of the Nevis samples (Table 1).

Glacial catchment integration

The penultimate and some earlier advances of the Wakatipu glacier have extended southward down the Mataura valley beyond the ultimate (Otiran) advance terminal moraine at the southern end of Lake Wakatipu (Figure 1). Pre-Otiran remnants of moraine or outwash sediment occur at various elevations up to 160 m above the present Mataura valley floor (Ashcroft 1964; Brockie 1973; McIntosh et al. 1990), and are locally auriferous. Outwash gravel correlated with the Athol Advance (approximately 200 ka) is preserved above 500 m on both sides of the Mataura valley at Athol (Figures 1 and 3). Brockie (1973) suggests that Nokomai Saddle (480 m) between the Mataura and the Nokomai valleys (Figure 3) would have been topped and cut by diffluent ice during the Athol Advance. There is no evidence to indicate whether the lower Nokomai valley was occupied by ice, but it must nevertheless have received glacially transported and/or fluvially redistributed sediment derived from Wakatipu glacier tributaries farther upstream. Clinozoisite, magnetite, type 1 garnets, greenschist facies schist, and hydrothermal Au-Ag alloy are common in several of these tributaries. In addition, the most important intermediate repository for type 2 (if from Fiordland) and type 3 (Stewart Island) garnets, the middle Tertiary transgressive marine sediments, are preserved in the middle arm of the Lake Wakatipu basin.

Projection of Brockie's (1973) profile of Athol advance outwash surfaces down the Mataura valley suggests that outwash sediment will have have dammed the Nokomai at its confluence with the Mataura. Up to 3 m of undated remnants of varved lake silt are preserved 120 m above the valley floor in the lower Nokomai, and could have been deposited during such events. Wedges of Mataura River-type gravel inter-fingered with the Nokomai gravel were encountered during mining of the lower Nokomai, and such deposits may have prograded for some distance up the lower Nokomai valley during earlier glacial cycles. Thus, glacial integration of catchments appears the most plausible mechanism to explain the presence of Au-Ag alloy and other allochthonous minerals and clasts in the Nokomai, irrespective of whether they entered the valley via Nokomai Saddle or the confluence with the Mataura. Presumably, however, their heavy mineral content has been reworked and reconcentrated into the fossil channel in the lower valley and, in turn, into the sediments of the lower Nokomai alluvial plain.

Hg association with Caples metavolcanics?

Marshall (1918) genetically associated Otago cinnabar occurrences with basic Cenozoic volcanics in East Otago (Coombs et al. 1986), believing that cinnabar deposits only occur in close proximity to these rocks. Although mercury-bearing minerals are commonly associated with igneous hydrothermal systems elsewhere (Rytuba and Heropoulos 1992), a more complete distribution of occurrences in Otago (e.g. Morgan, 1914; Marshall 1918; Henderson 1923; Healy 1936; Williams 1974a) does not support Marshall's volcanic association, because most occurrences are remote from volcanic centres. Williams (1974a) suggested that Marshall (1918) may have been correct in dissociating mercurous mineralisation from the gold scheelite paragenesis of the Otago Schist (Craw & Norris 1991). The widespread occurrence of detrital α-phase Au-Ag-Hg alloy in the Nevis and Nokomai, and the primary sources we infer in those catchments, suggest instead that a gold-mercury paragenesis may be appropriate in some parts of the schist belt.

Gold and scheelite veins in the Otago Schist occur in both Caples and Torlesse Terrane rocks but are more common in the latter (Figure 1) (see Mortimer 1993). Predominance of one or other of these minerals in veins is controlled more by local geochemical conditions at the site of deposition (Paterson 1986; Craw & Norris 1991) rather than by fluid characteristics or the composition of the schist protolith. Consequently, the gold-scheelite paragenesis is applicable to the whole of the schist belt. Primary cinnabar deposits in the Otago Schist occur only within the Caples Terrane, however, and all significant occurrences of detrital cinnabar, as well as the α-phase Au-Ag-Hg alloy described in this study, are found only in catchments draining Caples Terrane rocks. We therefore propose a gold-mercury 'sub-paragenisis' for the Caples Terrane. We suggest that Hg may be an important indicator element for primary gold deposits in Caples rocks, and should be cosidered in soil geochemistry and stream sediment sampling surveys during exploration for such deposits.

Conclusions

Gold in Quaternary placers in the Nevis and Nokomai valleys is dominantly α-phase Au-Ag-Hg alloy with less than about 10 wt.% Hg, which is interpreted to be derived from hydrothermal sources in western tributaries of the upper Nevis and eastern tributaries of the upper Nokomai. These and related sources may also have supplied the abundant cinnabar commonly associated with the Au-Ag-Hg alloy. Minor silver-grey-coloured, secondary Au-Ag-Hg alloy with up to about 38 wt.% Hg is present locally in the lower Nokomai alluvial plain. This alloy is interpreted to have formed in the lower Nokomai and/or adjacent tributary by diffusion between both detrital Au-Ag and α-phase Au-Ag-Hg alloys, and liquid Hg that is either hydrothermal in origin or derived from local breakdown of cinnabar.

Gold in the lower half of the Nokomai alluvial plain and adjacent abandoned channel is dominantly Au-Ag alloy, but minor α-phase Au-Ag-Hg alloy is also present in the latter. The Au-Ag alloy and associated magnetite, clinozoisite, well foliated schist boulders, and three types of garnet, are allochthonous to the Nokomai catchment. They were most likely derived from greenschist facies and sedimentary rocks many tens of kilometers north of the Nokomai catchment. They were introduced to the Nokomai in outwash or till during Quaternary advances of the Wakatipu Glacier, either via Nokomai Saddle on the western side of the valley, via the confluence with the Mataura, or both.

A gold-mercury 'sub-paragenisis' is proposed for the Caples Terrane. Hydrothermal cinnabar in the Otago Schist, and probably hydrothermal Au-Ag-Hg alloy as well, are restricted to the Caples Terrane, and one or both of these minerals should be expected to occur in placer deposits derived from Caples Terrane rocks.

References

Adams, C. J., 1981: Uplift rates and thermal structure in the Alpine Fault Zone and Alpine Schists, Southern Alps, New Zealand; in McClay & Price (Eds.), Thrust and nappe tectonics. Geological Society special publication, 211–222.

Ashcroft, N. M., 1964: A geomorphological reconnaissance of the upper Mataura district. Unpublished M.A. thesis held in the University of Otago Library: 101p.

Atanasov, V. A., Jordanov, J. A., 1983: Amalgams of gold from the Palakharya River alluvial sands, district of Sofia. Comptes rendus de l'Académie bulgare des Sciences 36: 465–468.

Atanasov, V., Jordanov, J. A., Vitov, O. C., Atanasov, A. V., 1988: Amalgams of gold in some of the Bulgarian alluvial sands. Annual of the Higher Institute of Mining and Geology (1987–1988), Sofia 34: 227–238.

Basu, K., Bortnykov, N., Mookherjee, A., Mozgova, N., Tsepin, A. I., 1981: Rare minerals from Rajpura-Dariba, Rajasthan, India II: Intermetallic compound $Ag_{74.2}Au_{16.4}Hg_{9.4}$. Neues Jahrbuch Fur Mineralogie Abhandlungen 141: 217–223.

Beanland, S., Barrow-Hurlbert, S. A., 1988: The Nevis-Cardrona fault system, Central Otago, New Zealand: Late Quaternary tectonics and structural development. New Zealand journal of geology and geophysics 31: 337–352.

Berman, H., Harcourt, G. A., 1938: Natural amalgams. American Mineralogist 23: 761–764.

Bishop, D. G., 1972: Progressive metamorphism from prehnite-pumpellyite to greenschist facies in the Dansey Pass area, Otago, New Zealand. Geological Society of America Bulletin 83: 3177–3198.

Black, J. G., 1885: Chemistry for the gold fields. Dunedin, Horseburgh. 569p.

Bradshaw, J. Y., 1989: Basement geology, northern Franklin Mountains, northern Fiordland, New Zealand, with emphasis on the origin and evolution of Fiordland granulites. Unpublished PhD thesis held in the University of Otago Library: 379p.

Brockie, W. J., 1973: Quaternary history of southern Wakatipu and the upper Mataura valley; in, McKellar, I. C. and Brockie, W. J. (eds.), Guidebook for excursion 8, Otago and Southland. IX International Union for Quaternary Research (INQUA) congress, Christchurch, New Zealand.

Brown, E. H., 1965: Metamorphic facies and structure of a region in eastern Otago, New Zealand. Unpublished PhD thesis held in the University of Otago Library: 157p.

Brown, E. H., 1967: The greenschist facies in part of East Otago, New Zealand. Contributions to mineralogy and petrology 14: 259–292.

Coombs, D. S., Cas, R. A., Kawachi, Y., Landis, C. A., McDonough, W. F., Reay, A., 1986: Cenozoic volcanism in North, East, and Central Otago. Royal Society of New Zealand bulletin 73: 278-312.

Cooper, A. F., 1970: Metamorphism, structure and post-metamorphic intrusives of the Haast River area, South Westland, New Zealand. Unpublished PhD. thesis held in the University of Otago Library: 331p.

Cooper, A. F., 1972: Progressive metamorphism of metabasic rocks from the Haast Schist Group of southern New Zealand. Journal of petrography 13: 457–492.

Craw, D., 1984: Lithologic variations in Otago Schist, Mt. Aspiring area, northwest Otago, New Zealand. New Zealand journal of geology and geophysics 27: 151-166.

Craw, D., Norris, R. J., 1991: Metamorphic Au-W veins and regional tectonics: mineralisation throughout the uplift history of the Haast Schist, New Zealand. New Zealand journal of geology and geophysics 34: 373-383.

Douglas, B. J., 1986: Lignite resources of Central Otago. Publication P104, N.Z. Energy Research and Development Committee, University of Auckland, Auckland, New Zealand, 368 p.

Falconer, D. M., 1987: Detrital and authigenic gold in quartz gravels, Belle-Brook, Southland. Unpublished Dip.Sci. thesis held in the University of Otago Library: 112p.

Frewin, M. O., 1987: Geology of the Anglem Complex, northern Stewart Island, New Zealand. Unpublished MSc. thesis held in the University of Otago Library: 192p.

Harrison, H. L. H., 1962: Alluvial mining for tin and gold. London, Mining Publications. 313p.

Hector, J., Skey, W., 1866: Supplementary report on Class I: Mining, quarrying, metallurgy, and mineral products. Appendix A in; New Zealand Exhibition, 1865; Reports and Awards of the Jurors. 371-452.

Healy, J., 1936: Whakaea Subdivision. New Zealand Geological Survey 30th annual report. 6-9.

Healy, R. E., Petruk, W., 1990: Petrology of the Au-Ag-Hg alloy and "invisible" gold in the Trout Lake Massive Sulphide deposit, Flin Flon, Manitoba. Canadian Mineralogist 28: 189-206.

Hem, J. D., 1970: Chemical behaviour of mercury in aqueous media. United States Geological Survey Professional Paper 713: 19–24.

Henderson, J., 1923: Cinnabar in Greenvale Survey District, near Waikaka, Southland. New Zealand Geological Survey 17th annual report. 12.

Hérail, G., Fornar, G., Viscarra, G., and Miranda, V., 1990: Morphological and chemical evolution of gold grains during the formation of a polygenetic fluviatile placer: the Mio-Pleistocene Tipuani placer example (Andes, Bolivia). Chronique de la Recherche Minierie 500: 41-49.

Hutton, C. O., Turner, F. J., 1936: The heavy minerals of some Cretaceous and Tertiary sediments from Otago and Southland. Transactions of the Royal Society of New Zealand 66: 255-275.

Hutton F. W., Ulrich G. H. F., 1875: Report on the geology and goldfields of Otago. Mills Dick and Co., Dunedin. 245p.

Kerr, L.C., Craw, D., Norris, R.J., Youngson, J.H., Wopereis, P. 2000: Structure, geomorphology, and gold concentration in the Nokomai valley, Southland, New Zealand. New Zealand Journal of Geology and Geophysics 43 (in press).

Kerr, L. C.; Wopereis, P. 1996: Sources of alluvial gold, Nokomai catchment, northern Southland. Proceedings of the Australasian Institute of Mining and Metallurgy, 29th annual conference, Greymouth: The changing face of West Coast mining. 153-158.

Knight, J. B., Mortensen, J. K., Morrison, S. R., 1994: The shape and composition of lode and placer gold from the Klondike district, Yukon, Canada. Department of Indian and Northern Affairs, exploration and geological services division, Yukon Region, Bulletin 3, p. 1-141.

Le Masurier, W. E.; Landis, C. A., 1996: Mantle-plume activity recorded by low-relief erosion surfaces in West Antarctica and New Zealand. Geological Society of America bulletin 108: 1450-1466.

McIntosh, P. D., Eden, D. N., Burgham, S. J., 1990: Quaternary deposits and landscape evolution in northeast Southland, New Zealand. Paleogeography, Paleoclimatology, Paleoecology 81: 95-113.

Marshall, P., 1918: The geology of the Tuapeka District. New Zealand Geological Survey bulletin 19: 79p.

Mitchell, M. J., 1996: Alluvial platinum-group minerals from southern New Zealand. Unpublished PhD thesis held in the University of Otago Library.

Morgan, P., 1914: The Waikaka gold-mining field. 6-9. New Zealand Geological Survey 8th annual report. 147-152.

Mortimer, N., 1993: Geology of the Otago Schist and adjacent rocks. Scale 1: 500 000. Institute of Geological and Nuclear Sciences geological map 7. 1 sheet. Institute of Geological and Nuclear Sciences Ltd, Lower Hutt, New Zealand.

Mortimer, N., in press: Mineral compositional variation in the Otago Schist, New Zealand: implications for recrystallisation and exhumation. Geologische Rundschau.

Norris, R. J., Carter, R. M., Turnbull, I. M., 1978: Cainozoic sedimentation in basins adjacent to a major continental transform boundary in southern New Zealand. Journal of the Geological Society of London 135: 191-205.

Paterson, C. J., 1986: Controls on gold and tungsten mineralization in metamorphic-hydrothermal systems, Otago, New Zealand. Geological Association of Canada special paper 32: 25–39.

Peden, R., 1988: Dynamic metamorphism within the Rakeahua batholith. Mason and Doughboy Bay region, Stewart Island. Unpublished MSc. thesis held in the University of Otago Library: 87p.

Rytuba, J. J., Heropoulos, C., 1992: Mercury - An important byproduct in epithermal gold systems; in, DeYoung, J. H. Jr., Hammarstrom, J. M., (eds.), Contributions to commodity geology research. United States Geological Survey Bulletin 1877: D1-D8.

Sharp, J. R., 1993: The geology of the Tapui Glauconitic Sandstone: Unpublished MSc. thesis held in the University of Otago Library: 161p.

Stirling, M.W., 1990: The Old Man Range and Garvie Mountains: tectonic geomorphology of the Central Otago peneplain, New Zealand. New Zealand Journal of Geology and Geophysics 33: 233-244.

Sutherland, R., 1996: Transpressional development of the Australia-Pacific boundary through southern South Island, New Zealand: constraints from Miocene-Pliocene sediments, Waiho-1 borehole, South Westland. New Zealand journal of geology and geophysics 39: 251-264.

Turnbull, I. M., 1980: Geological map of New Zealand 1:50 000 Sheet E42 AC Walter Peak (west); map (1 sheet) and notes (19 p.). Wellington, Department of Scientific and Industrial Research.

Turnbull, I. M., 1988: Geological map of New Zealand 1:63 360 Sheet S133 Cromwell; map (1 sheet) and notes (43 p.). Wellington, Department of Scientific and Industrial Research.

Turnbull, I. M., Barry, J. M., Carter, R. M., Norris, R. J., 1975: The Bobs Cove Beds and their relationship to the Moonlight Fault Zone. Journal of the Royal Society of New Zealand 5: 355-394.

Turnbull, I. M., and Forsyth, P. J., 1988: Queenstown: A Geological Guide. Geological Society of New Zealand Guidebook No. 9.48 p.

White, S. R., 1996: Composition and zoning of garnet and plagioclase in Haast Schist, northwest Otago, New Zealand: implications for progressive regional metamorphism. New Zealand Journal of Geology and Geophysics 39: 515-531.

Williams, G.J., 1974a: Economic geology of New Zealand. Australasian Institute of Mining and Metallurgy Monograph 4, 490 p.

Williams, G. J. 1974b: Cenozoic geology of the lower Nevis basin, with special reference to shale deposits. New Zealand Department of Scientific and Industrial Research bulletin 212: 36p.

Youngson, J. H., 1996: Natural and anthropogenic gold-silver-mercury amalgams in Central Otago placers. Dunedin conference 1996; Geological Society of New Zealand miscellaneous publication 91A: 182 (abstract).

Youngson, J. H., 1998: The use of fluvial gold morphology in placer and primary source exploration. Proceedings of the Australasian Institute of Mining and Metallurgy, 31st annual conference, Christchurch: Mining and the Environment. 145-157.

Youngson, J. H., in review: Occurrence, composition and morphology of hydrothermal, secondary and synthetic gold-silver-mercury alloys. Submitted to Economic Geology.

Youngson, J. H., Craw, D., 1995: Evolution of placer gold deposits during regional uplift, Central Otago, New Zealand. Economic geology 90: 731-745.

Youngson, J. H., Craw, D., 1996: Recycling and chemical mobility of alluvial gold in Tertiary and Quaternary sediments, Central and East Otago, New Zealand. New Zealand journal of geology and geophysics 39: 493-508.

Youngson, J. H., Craw, D., 1999: Variation in placer style, gold morphology, and gold particle behaviour down gravel bedload rivers: an example from the Shotover/Arrow-Kawarau-Clutha River system, Otago, New Zealand. Economic geology 94: 615-634.

Youngson, J. H., Craw, D., Landis, C. A., Schmitt, K. R., 1998: Redefinition and interpretation of late Miocene-Pleistocene terrestrial stratigraphy, Central Otago, New Zealand. New Zealand journal of geology and geophysics 41: 51-68.

Authors

JOHN YOUNGSON is a Research Fellow at the University of Otago. He and Associate Professor Dave Craw are carrying out ongoing research into the formation and distribution of placer gold deposits, with particular emphasis on the Otago, Southland and Westland deposits.

PAUL WOPEREIS is a consultant geologist with extensive experience in placer gold deposits. He worked with L&M Mining during the period of their commercial operations in the Nevis and Nokomai valleys, and is currently independent.

LUKE KERR carried out his MSc thesis project in the Nokomai during the mid 1990s, and worked part-time for L&M Mining on their mapping, soil sampling and stream sediment sampling in the catchment. He is currently working for Striker Resources on a diamond project in Australia.