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The "Donauplatin": source rock analysis and origin of a distal fluvial Au-PGE placer in Central Europe

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Abstract The mineral assemblage and the sedimentological characteristics of the "Donauplatin" (Danubian fluvial placer containing platinum-group elements (PGE) and gold (Au)) are described for the first time in connection with upstream reference placer deposits near the potential source area in tributaries of the River Danube/Donau. Granulometric and morphometric data have been obtained using the CCD-based CAMSIZER technique. The platinum-group minerals (PGM; iridium, osmium, unknown iridium-osmium-sulfide, ruthenium-osmium-iridium alloys, platinum-iron alloys, iridium-bearing platinum, sperrylite) have been derived from ultramafic magmatic rocks, probably belonging to the ophiolitic series in the Tepla Barrandian unit of the Bohemian Massif. The Au-Pd-Cu compounds in the placer originated from dynamo-metamorphogenic processes in a sulfur-deficient environment at the SW edge of the Bavarian Basement. Gold in the "Donauplatin" has been reworked from a "secondary" or intermediate repository of lateritic gold (Boddington-type). Its primary source is supposed to be of orogenic origin. Provenance analyses of the associated non-heavy minerals point to high-pressure metamorphic rocks, igneous rocks (monazite) and high-temperature metamorphic rocks (750° to 850°C, zircon morphology). Garnet compositions indicate that meta(ultra) basic igneous rocks, calc-silicate rocks and skarns prevailed over paragneisses in the provenance area. Extraterrestrial processes creating the well-known Ries impact crater in the environs of Nördlingen during the Miocene have a minor share in the PGE budget by delivering molybdenum-ruthenium-osmium-iridium alloys and iridium solid-solution series (s.s.s.) minerals. Judging by the heavy mineral suites, Saxothuringian source rocks of the NE Bavarian Basement connected with the Donau River via the Naab River drainage system have not contributed to the element budget of the "Donauplatin" under study. Stream sediments which have been derived from this provenance area are characterized by low-temperature (LT) crystalline rocks and a considerable proportion of pegmatitic and metabauxitic material lacking in the Holocene sediments of the "Donauplatin".

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Introduction

The "Rheingold" is well entrenched in literature and music and is known to geoscientists as the most distal part of the Alpine alluvial-fluvial gold placer system, starting off high up in the Swiss Alps, in the Gotthard Massif (Jaffé 1986, Weibel et al. 1998, Walter and Dill 1995, Dill 2008). But what about the "Donauplatin"; i.e. Danubian Au-PGE placer mineralization? It was not until 2007, that geo-scientific information has been made available on this placer mineralization along the leg of the river Donau (Danube) between Regensburg and Passau, Germany (Dill et al. 2007a, Fig. 1). Mineralogical or sedimentological data on the distribution of PGM in this fluvial drainage system are neither known upstream nor downstream of the study site.

By contrast, PGM-bearing mineral assemblages have been described from the uplifted basement blocks bordering the Danubian fluvial drainage system towards the N and the S. Carboniferous and Permian sedimentary sequences in the Lugicum of the Bohemian Massif host Au placers with up to 10 wt % Pd accommodated in native Au together with

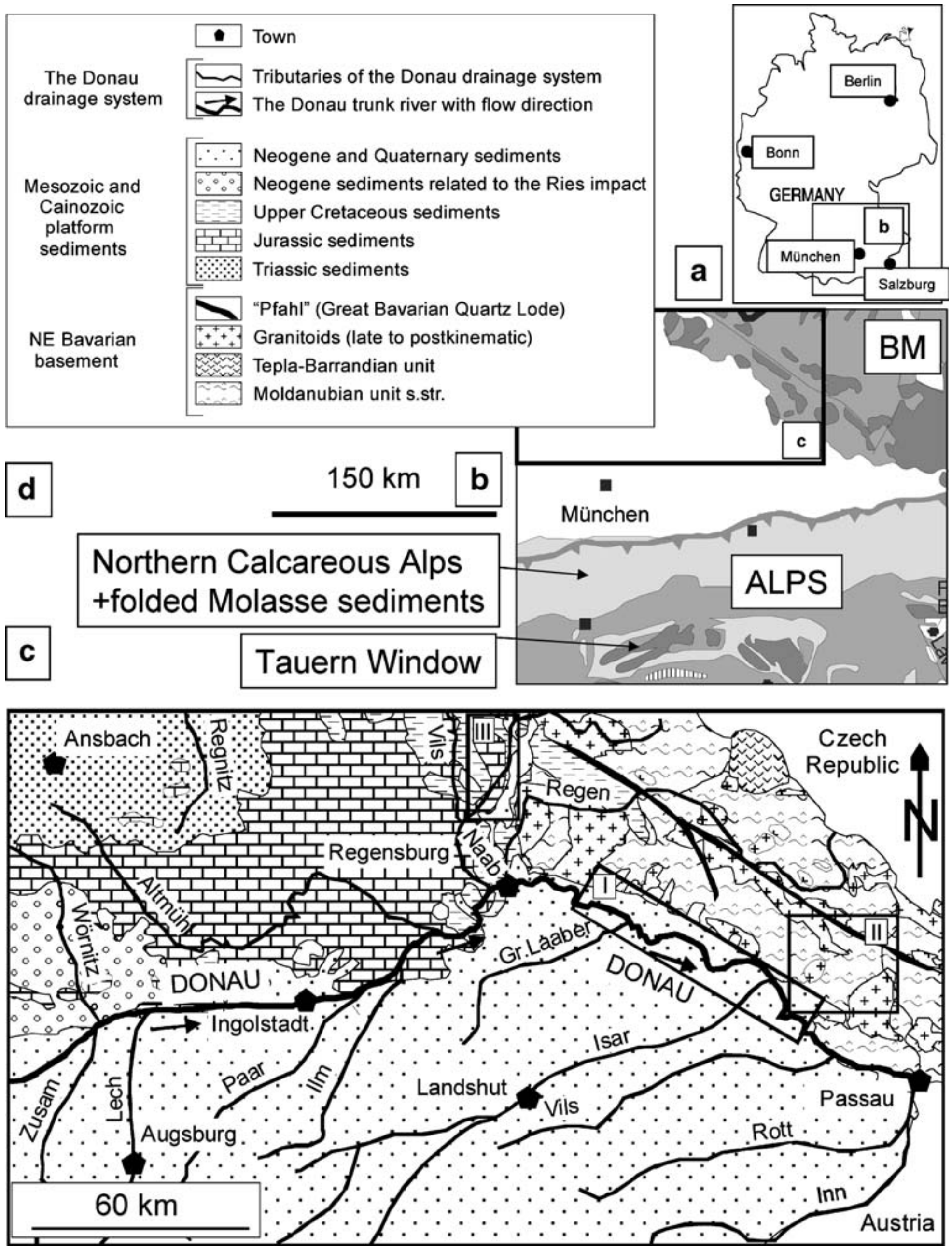


Fig. 1 Location and geological setting of the study area, **a** Location of the study area in Germany indicated by the framed area **b** Location of the study area relative to the two potential provenance areas for Au and PGE in the placer deposits (BM Bohemian Massif, ALPS Alpine mountain range) Two major geological units are marked by arrowheads in the Alpine mountain range. The location of Fig. 1c is denoted by the framed area **c** Geological setting of the "Donauplatin" placers between Regensburg and Passau (sampling site) (redrawn from the official geological map 1:500000 issued by the former Geological Survey of Bavaria). The target area I along the River Danube is denoted with the Roman numeral I. Area II denotes the sampling area in the environs around Tittling where Tertiary sediments cover the basement rocks. Area III lies within the upper reaches of the Naab River drainage system **d** Legend of Fig. 1c

some rare Pd minerals (Malec and Veselovsky 1985). In the Eastern Alps, PGE mineralization has been known for quite a long time from podiform chromitites in the Hochgrössen and Kraubath ultramafic massifs, Austria (Thalhammer et al. 1990, Malitch et al. 2001, 2003a). Even the platform sediments cannot be neglected when it comes to delineating a potential source area of PGE for the "Donauplatin" placer as demonstrated by the numerous impact structures upstream of the sampling sites, some of which are still the subject of heated debates regarding their origin in the course of extraterrestrial bodies slamming the Earth (Rutte 1971, Hofmann 1973, Hüttner and Reiff 1977, Schmidt and Pernicka 1994, Stöffler et al. 2002). PGE finds have so far not been recorded from any of these extraterrestrial features in Germany but are known to occur in many meteorites and the ejecta produced by such impacts. The most hotly debated event of this type is the one accountable for the iridium anomaly at the K/P (Cretaceous-Paleogene boundary) (Robin et al. 1991).

This paper presents comprehensive mineralogical data for Holocene Au-PGE placer mineralization in the Donau and some upstream proximal placer deposits. The Au-PGE placer mineralization, although subeconomic in size and grade, may be used as an ore guide leading exploration geologists to potential primary deposits and also add information to the geodynamic and paleogeographic interpretation of the source rock areas as well as the evolution of the host drainage system. This study may also add some new information to the discussion on impacts found across the Mesozoic and Cenozoic platform sediments in the Alpine foreland basin where the true nature of crater-like depressions is often difficult to explain and a detailed analysis of heavy minerals may be a clue to solve this problem. The mineralogical study is supplemented by sedimentological investigations, which may help to reveal the origin of mixed-type Au-PGE placer deposits elsewhere, applying for the first time CCD-based CAMSIZER techniques for grain size and morphology measurements to these precious metal placer deposits. Previous studies of PGE placers have exclusively paid attention to the chemical composition of PGM particles but have not addressed these special issues of grain size and morphology to constrain the mode of placer deposition (Wilde et al. 1989, Cabri et al. 1996, Malitch and Merkle 2004).

Geological setting and sampling

The evolution of the Donau river drainage system is very complex with numerous changes of the paleocurrent directions during the Cenozoic. The present-day Donau draining to the Black Sea acquired its final shape during the waning stages of the glacial periods (Villinger 1998). The Quaternary alluvial-fluvial plain of the Donau which was sampled during this study is underlain by siliciclastic and calcareous Mesozoic platform sediments and Paleogene and Neogene sediments of the Alpine foreland basin which are intersected by the modern Donau River at various sites (Fig. 1). The Pliocene was a period of time crucial for the shaping of the Donau-Naab river alluvial-fluvial system under study when a vast gravel plain developed in the environs of Regensburg at the confluence of both rivers (Stückl 1991). The NE Bavarian basement was uplifted *en bloc* (Semmel 1996). The crystalline basement rocks of the Bohemian Massif covering a large area north of the sampling site I consist of paragneisses, Late Variscan granites and some basic and ultrabasic igneous rocks (Fig. 1). They are brought in direct contact with the fluvial sediments of the modern Donau trunk river along the Donau Fault Zone. By contrast, the Alpine mountain range is only linked up with the Donau drainage system via several tributaries such as the rivers Inn, Isar and Lech (Fig. 1). The northern edge of the Alpine mountain range is characterized by limestones and folded Molasse sediments, mantling a crystalline core zone exposed within and around the Tauern Window, an area that deserves particular attention as a potential provenance area for the PGE heavy minerals of the "Donauplatin". Sampling was carried out within the Holocene floodplain sediments of the Donau River between Regensburg and Passau. Gravel and coarse sands outcropping along the thalweg and in sand pits were sampled for their heavy mineral accumulations. Encouraged by the discovery of PGM in the "Donauplatin" placer, sampling was also directed to the southern Bayerischer Wald where thick Neogene argillaceous and arenaceous sediments cover migmatitic gneisses and granites (Koch et al. 1997). A third sampling area lies within the Naab River Drainage system (site III) one of the most important tributaries upstream of the "Donauplatin" delivering debris from the Saxothuringian zone representing the northernmost geodynamic parts of the Bavarian basement.

Methodology

20 concentrates from five recent placer deposits (two: site I, two: site II, one: site III) were sieved and the grain size fraction 63 to 1000 μm was used for follow-up heavy mineral analyses. Neither grinding in a crusher nor diluted HCl acid were used to disintegrate the rocks in order to avoid leaching phosphates and provoking man-made changes to the grain surfaces and morphology. During routine analyses, the heavy minerals (density>2.9 g/ cm^3) were extracted by means of Na-polywolframate. Prior to the analytical work, PGM species need to be concentrated by time-consuming hand-picking using their color and shape for identification. After removal of iron oxide, coating mineral grains, with Na dithionite, translucent heavy minerals were mounted on glass disks using Canada balsam. They were identified under a polarisation microscope. For reasons of quantity, the analysis of PGM species by means of electronmicroprobe, successfully applied to alluvial-fluvial Sn- and Ti placer deposits in the neighboring NE Bavarian Basement, could not be applied to these samples from the fluvial Donau stream sediments (Dill et al. 2006, 2007b). The scanning electron microscope FEI QUANTA 600 FEG with an energy-dispersive system (SEM-EDX), was used for mineral identification and imaging. The SEM QUANTA 600 FEG was linked with an EDX System (GEMINI) allowing analysis under three different pressure regimes: High vacuum (ca 10^{-6} mbar), (2) LowVac (approx. 0.1 to 1.0 mbar), (3) ESEM (approx. 1 to 30 mbar). Due to the use of low-vac conditions these minute hand-picked particles need not be sputtered prior to analysis. The data presented may be taken as semi-quantitative but are sufficient for a denomination of the various minerals. The different heavy mineral separates have also been passed through a CAMSIZER for grain size and morphological analyses. The data are denoted in the common way in terms of sphericity and roundness values, using the schemes and comparison charts elaborated by Illenberger (1991) and Tucker (2001) for grain morphology. The CAMSIZER® measuring system is based on digital

image processing. The bulk material flow falls between a light source and cameras. All particles are optically recorded, digitized and processed in the connected computer.

Results

Mineralogical and chemical composition of the PGE- Au placer mineralization ("Donauplatin")

Gold Gold grains make up the lion share among precious metal compounds in the PGE- and Au placers exceeding more than 90 % of the heavy mineral grains (Fig. 2a). Gold fineness is the highest ever found in placers of the NE-Bavarian Basement, proper, and in placers of the foreland sediments deposited to the immediate west of the basement. By means of SEM-EDX no impurities could be detected in the gold grains. In polished reference sections of gold grains no significant compositional variation from the rim towards the core was observed (Fig. 3). Whenever inclusions, coatings or minerals, e.g., quartz or arsenopyrite were irregularly intergrown with gold grains, these minerals were identified in the placer mineral assemblage simply by means of SEM-EDX.

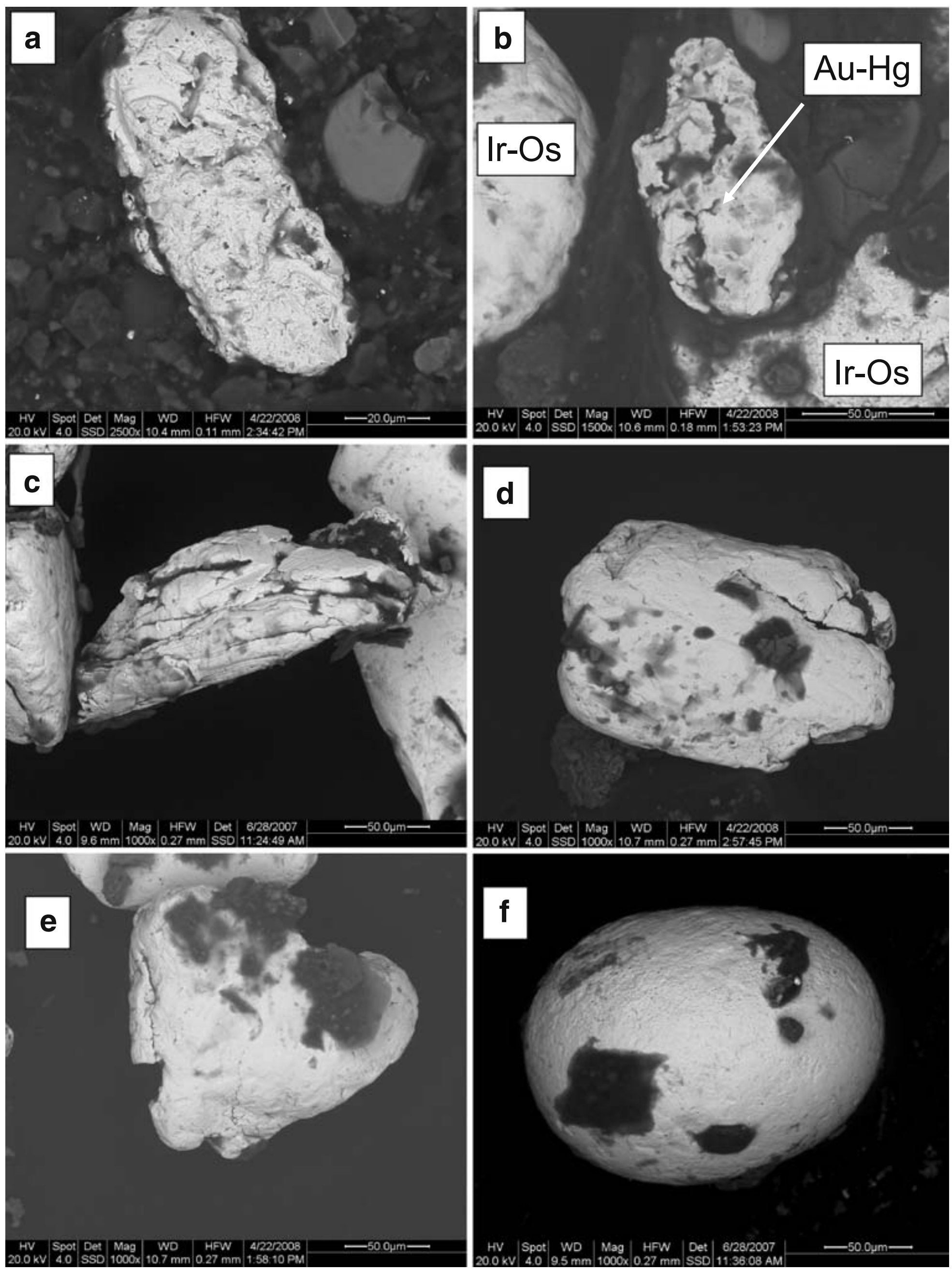


Fig. 2 Secondary electron images of gold and PGE placer minerals. Minerals were identified using EDX, **a** Subangular gold grain which has been scratched and hammered on transport **b** Gold amalgam with typical pock-marks and knobs ("Au-Hg") besides a rounded and subrounded grain of an iridium-osmium alloy ("Ir-Os") **c** Gold-palladium-copper alloy (Au-Pd-Cu alloy) **d** Iridium (100 at. % Ir) **e** Iridium-osmium alloy (40% Ir, 60% Os) **f** Unknown Ir-Os sulfide ("Ir-bearing erlichmanite")

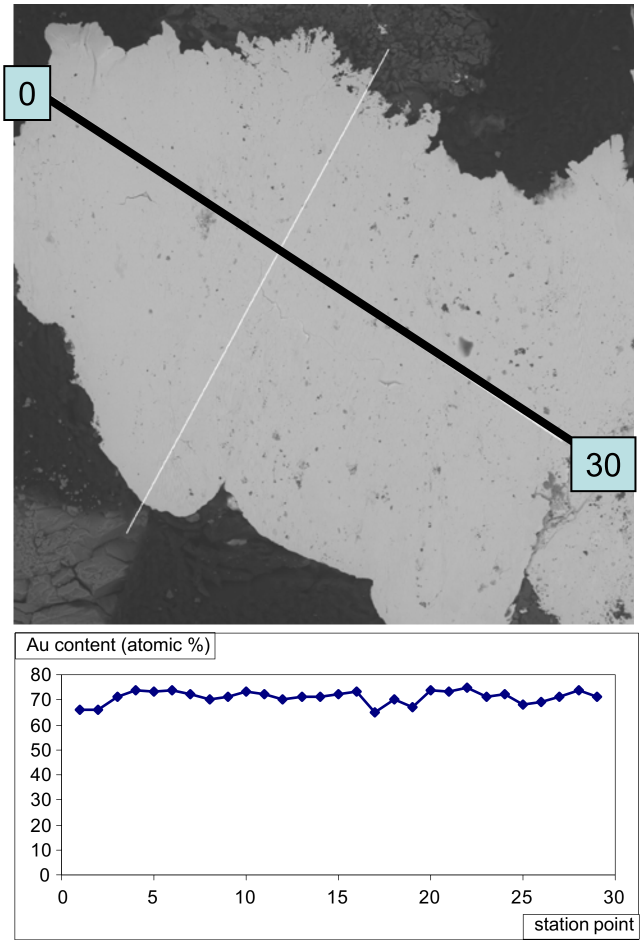


Fig. 3 Line scan by means of SEM-EDX of a polished section of a fluvial placer particle containing gold and silver as main components in order to demonstrate the homogeneity of placer gold

Gold amalgam Porous aggregates rich in gold and mercury, with gold in the range 40 to 70 at. % Au and mercury between 30 and 60 at. % Hg have been identified in the heavy mineral suite. Other alloy materials such as Cu, Ag or PGE have not been detected in this porous gold amalgam (Fig. 2b, Table 1).

Gold-palladium-copper alloys Gold is also alloyed with PGE and base metals. The alloy material found in this chemical compound is Pd and Cu that yield an approximated formula of $Au_{75}Pd_{15}Cu_{10}$ and thus qualifies for being named gold-palladium-copper alloy (Fig. 2c, Table 1). Palladium is present with 2 % among the PGE and bridges the gap between the gold- and PGE-bearing compounds (Table 2).

Iridium-osmium alloys and sulfides Unlike palladium, iridium (43 vol. %) and osmium (41 vol. %) take a prominent position among the PGM (Table 2). Iridium (up to 10 at. % Os) and Osmium (up to 10 at. % Ir) show well-preserved crystal morphology, with only some beveled edges. Iridium-osmium alloys mostly occur as triangular grains with Os contents between 80 to 20 at % Os and Ir contents between 80 and 20 at. % Ir (Fig. 2e). Harris and Cabri (1991) have discredited terms like “iridosmine” and “osmiridium”. Therefore in the succeeding paragraphs those mineral grains are referred to as iridium-osmium alloys. They are called iridium or osmium, respectively, as they contain only Ir or Os or come close to one of these end members (less than 10 at %). An Ir-Os sulfide was identified which does not match any of the PGM recorded by Cabri (2002). As to the composition, this sulfide might be close to erlichmanite [OsS_2], which has an Ir-enriched member known from the ultramafic rocks at Osthammeren, Norway, by Nilsson (1990).

Ruthenium molybdenum and ruthenium-iridium-osmium alloys Ruthenium, present at an amount of 6 vol. % among PGM, is mainly alloyed with iridium and osmium which has almost the same hardness and crystallized in the same crystallographic class as ruthenium-iridium-osmium alloys (Tables 1, and 2, Fig. 4a). Skimming the list of PGM published by Cab*ri* (2002), molybdenum is not among the elements normally found to be alloyed with PGE in the lithosphere. However, there is a still unnamed Mo-Ru-Fe-Ir-Os alloy coded IMA 2007–029 (Fig. 4b) (Ma and Rossman 2007).

Platinum minerals Like ruthenium, platinum has also been found alloyed with iridium and with osmium (Fig. 4c, d, Table 1). In the placer mineralization under study the Pt/Ir ratio of grains is 4:1. In the platinum alloys, osmium is always associated with iron. There are also pure platinum-iron alloys free of iridium and osmium (Fig. 4e). Sperrylite is the only arsenide identified among the PGM in the “Donauplatin” (Fig. 4f).

Silicates Garnet is the most common heavy mineral silicate phase among the placer minerals. Based upon their chemical composition, five groups may be distinguished, with four solid solution series (s.s.s.) dominated by almandine (almandine, almandine-grossularite-spessartite s.s.s., almandine-grossularite s.s.s., almandine-pyrope s.s.s.) and one dominated by pyrope (pyrope-almandine-grossularite s.s.s.) (Table 3). All garnet grains of the “Donauplatin” are present in the placer deposits as water-worn anhedral to subhedral isometric grains and therefore no detailed study of their crystal morphology can be carried out here. Unlike garnet s.s.s., zircon grains allow for a typological discrimination and an establishment of various zircon types, due to the strong resistance of zircon against weathering and post-depositional alteration as well as its extreme variability in crystal morphology that has been used for correlating the crystal morphology with the environment of formation (Pupin 1980, Friis et al. 1980, Bossart et al. 1986, Benisek

Table 1 Mineralogical and qualitative chemical composition of the "Donauplatin"

Mineral	Crystal system	Hardness	Cleavage	Mean Sphericity	Mean size (μM)	Shape class	Au	Ir	Os	Ru	Pt	As	Fe	Hg	Mo	Pd	Cu	S	Provenance
Gold	isometric - hexoctahedral	3	none	0.820	230	subangular to angular	+												Lateritic gold (strongly reworked)
Gold amalgam	isometric - hexoctahedral	3	none	0.704	170	subrounded to angular	+							+					Artificial product from gold recovery
Gold-palladium-copper alloys	unknown	unknown		0.394	200	subangular	+									+	+		Dynamo-metamorphogenic (shear-zone hosted, sulfur-deficient environment) Approx. 600°c
Iridium	isometric - hexoctahedral	6.5	none	0.624	213	subrounded		+											Ophiolite –related Subtype "chindwin basin"+ "aikor river"
Iridium-osmium alloys	hexagonal -	6.5	{0001} perfect	0.645	196	rounded to subangular		+	+										Ophiolite –related Subtype "chindwin basin"+ "aikor river"
Osmium	hexagonal	6.5	{0001} perfect	0.833	185	subrounded			+										Ophiolite –related Subtype "chindwin basin" + "aikor river"
Iridium-osmium-sulfide (unknown)	unknown	unknown	unknown	0.818	206	well-rounded		+	+									+	? (erlichmannite ophiolite –related)
Ruthenium-iridium-osmium alloys	hexagonal	7	perfect	0.786	170	rounded		+	+	+									Ophiolite –related Subtype "chindwin basin"+ "aikor river"
Molybdenum-ruthenium-iridium-osmium alloys	hexagonal	unknown	unknown	0.946	206	rounded		+	+	+					+				Impact-related Subtype "allende meteorite"
Platinum-iron alloys	isometric - hexoctahedral	5	unknown	0.718	195	rounded			+		+		+						Ophiolite –related Subtype "New Caledonia"
Platinum- iridium alloys	isometric - hexoctahedral	4.5	unknown	0.724	227	subrounded		+			+								Alaskan-type-related Subtype "Tulameen River"
Sperrylite	isometric - diploidal	6.5	unknown	0.769	87	subrounded					+	+							Various primary PGE deposits

Mineralogy of Au and PGM

a. Crystal system, hardness, cleavage (references: Ramdohr and Strunz 1978, Cabri et al. 1996, Cabri 2002)

b. Sphericity, mean size (μm) and roundness of grains

c. Major chemical components

Table 2 Relative proportion of PGM species (“Donauplatin”)

Quantity	Vol. %
Iridium-bearing particles	43
Osmium-bearing particles	41
Platinum-bearing particles	8
Ruthenium-bearing particles	6
Palladium-bearing particles	2

and Finger 1993, Bingen et al. 2001). In the “Donauplatin” two different types of detrital zircon were identified, whose shape is depicted in the common notation, using the Miller indices (Fig. 5a, b). Type Ia forms slender prisms with the faces {100}≥{110} and bipyramids {101}≥{211}, whereas type II shows an enlargement of faces {100} relative to the size of faces {110}. The pyramids are less well preserved and therefore similar face relationships as for type I cannot be provided. A very rare detrital constituent in the “Donauplatin” is amphibole. Rare light minerals such as quartz, albite and anorthite may also be present in the heavy

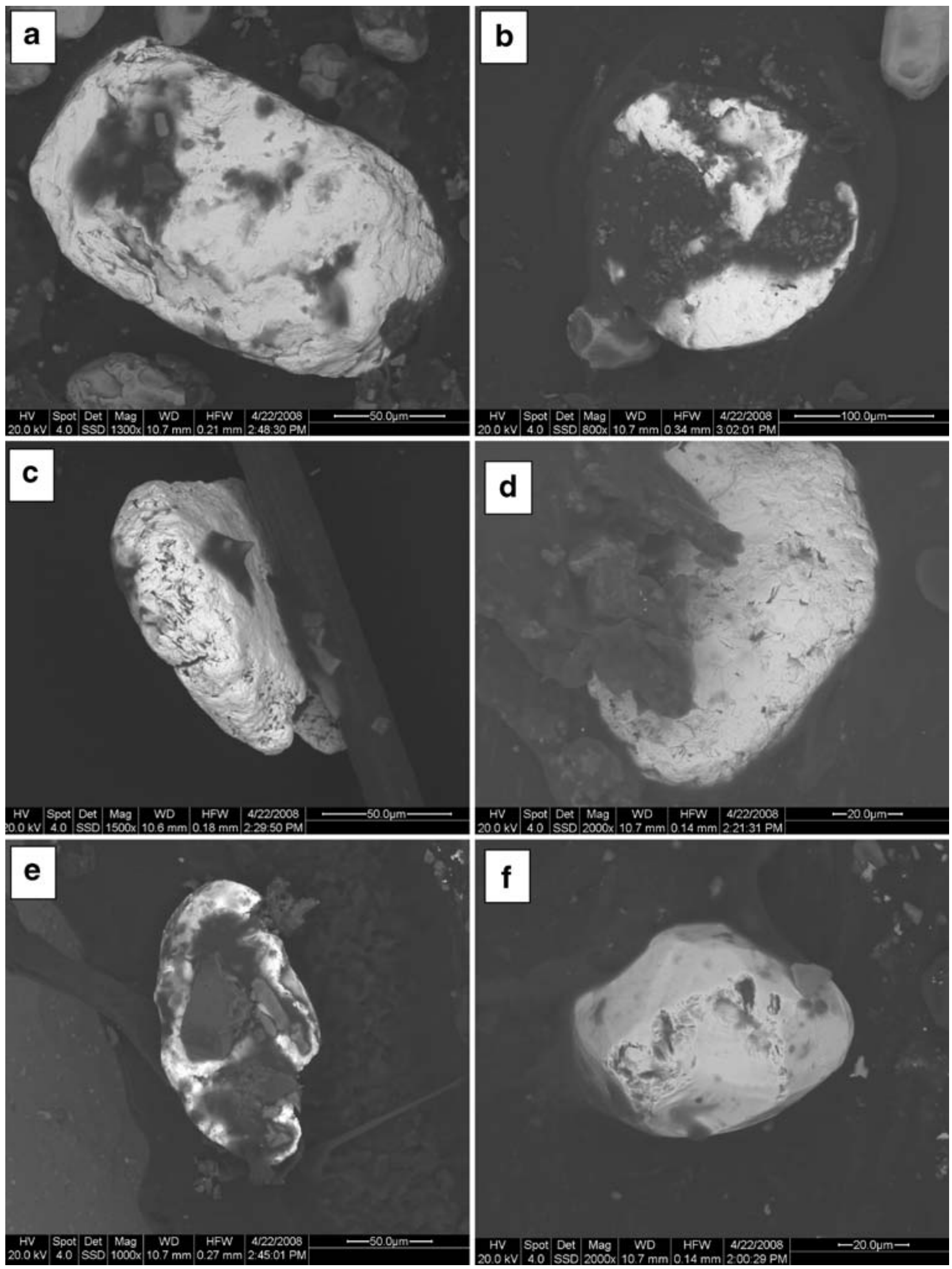


Fig. 4 Secondary electron images of PGE placer minerals. Minerals were identified using EDX **a** Ruthenium-iridium-osmium alloy (50 % Ru 40 % Os 10 % Ir) **b** Molybdenum-ruthenium-iridium-osmium alloys (40 % Mo 20 % Ru 20 % Os 20 % Ir) **c** Platinum-iridium alloy (20% Ir 80 % Pt) **d** Platinum-iron alloy osmium-bearing (30 % Os 50 % Pt 20 % Fe) **e** Platinum-iron alloy (80 % Pt 20 % Fe) **f** Sperrylite

Table 3 Minerals associated with Au and PGM species. Intergrowth and varieties denote solid solution series (s.s.s.) of minerals, morphological differences and intergrowth of heavy minerals with light minerals. Composition of garnet is based on SEM-EDX analysis

Associated minerals	Intergrowth and varieties	Provenance
Garnet	Almandine-enriched	Paragneisses (metapelitic rocks)
	Almandine-grossularite-spessartite s.s.s	Calcsilicate rocks to skarn
	Almandine-grossularite s.s.s.	Calcsilicate rocks
	Almandine-pyrope s.s.s.	Metabasic igneous rocks
	Pyrope-almandine-grossularite s.s.s.	Metaultrabasic igneous rocks
Zircon	Type Ia: {100}≥{110} - {101}≥{211}	Type Ia: 750°C
	Type II: {100} >> {110}	Type II: 850°C
Amphibole		No source rock indication
Monazite- (Ce)	Type I: monazite-(Th)	Type: I: igneous (or metamorphic)
	Type II: monazite-(Th-U)	Type II: HP metamorphics
	Type III: monazite-(U-Th)	Type III: hydrothermal
Xenotime-(Y)		No source rock indication
Goethite	Overgrowth on albite, anorthite, calcite, Fe-free dolomite	Limestones and dolomites
Hematite		No source rock indication
Ilmenite	Mn-free ilmenite	Limited source rock indication
	Pyrophanite-ilmenite s.s.s.	Quartzose shear zones late granitic
Rutile	Often intergrown with quartz	No source rock indication
Cassiterite	Cornish-type transitional into needle tin	Medium to low-temperature granite-related Sn mineralization
Chromium-Iron melting drop		Man-made alloy smelting
Chromium-bearing magnetite		Probably man made / ophiolite-hosted chromium mineralization

minerals concentrates owing to encrustations by "limonite" that increased the specific gravity of grains.

Phosphate Monazite is present among the transparent heavy minerals of the "Donauplatin" in almost equal amounts as zircon. For morphological studies, the phosphates, however, are less attractive than zircon due to the stronger attrition of the mineral grains on transport. The low morphological diversity among the monazite grains is compensated by the variegated chemical signature which allows for a tripartite subdivision (the marker elements are listed in brackets, e.g. monazite-(Th)): monazite I (Th), monazite II (Th>U), monazite III (U>Th) (Table 3, Fig. 6a). Monazite is associated with xenotime-(Y) a rather rare detrital component devoid of any outstanding morphological or compositional characteristics that might be instrumental to provenance analysis.

Oxide Rutile and ilmenite are the most common opaque or semi opaque heavy minerals in the "Donauplatin" placer. One type of ilmenite, has Mn-contents below the detection limit of the SEM-EDX , the other one up 10 % pyrophanite component. Cassiterite is a rare detrital mineral but from the morphological point of view it is almost as important as zircon (Fig. 6b). It was more severely affected by corrosion during transport than zircon but has its morphology still well preserved so as to allow for a classification of cassiterite types (Dill 1985, Dill et al. 2006). Cassiterite crystals are normally prismatic with the pyramid equal to the prism in size (Fig. 6b). This type of cassiterite falls between the so-called Cornish — type cassiterite and the well-known "needle tin". As such, this type of cassiterite may well be distinguished from the twinned aggregates (in German: "Visiergraupen") scattered in the stream sediments in creeks intersecting the crystalline rocks of the Hagendorf-Pleystein pegmatite province (Dill et al. 2006). Apart from goethite and hematite, which are ubiquitous, two Fe oxides warrant mentioning for their chemical composition and morphology. Iron-chromium oxides occur as small globules (Fe:Cr=5.7 : 1) and irregularly-shaped aggregates (Fe:Cr=3.9:1). No other elements could be determined by SEM-EDX and, hence, the aggregates were named "chromium magnetites". Placing this term between inverted commas seems appropriate, because it is meant to reflect the chemical composition of a compound which cannot claim to be of geogene origin and thus termed a mineral in the strict sense.

Mineralogical and chemical composition of the Au placer mineralization of the Bayerischer Wald

Gold Gold grains from the Bayerischer Wald are compositionally not at variance with the gold grains recorded from

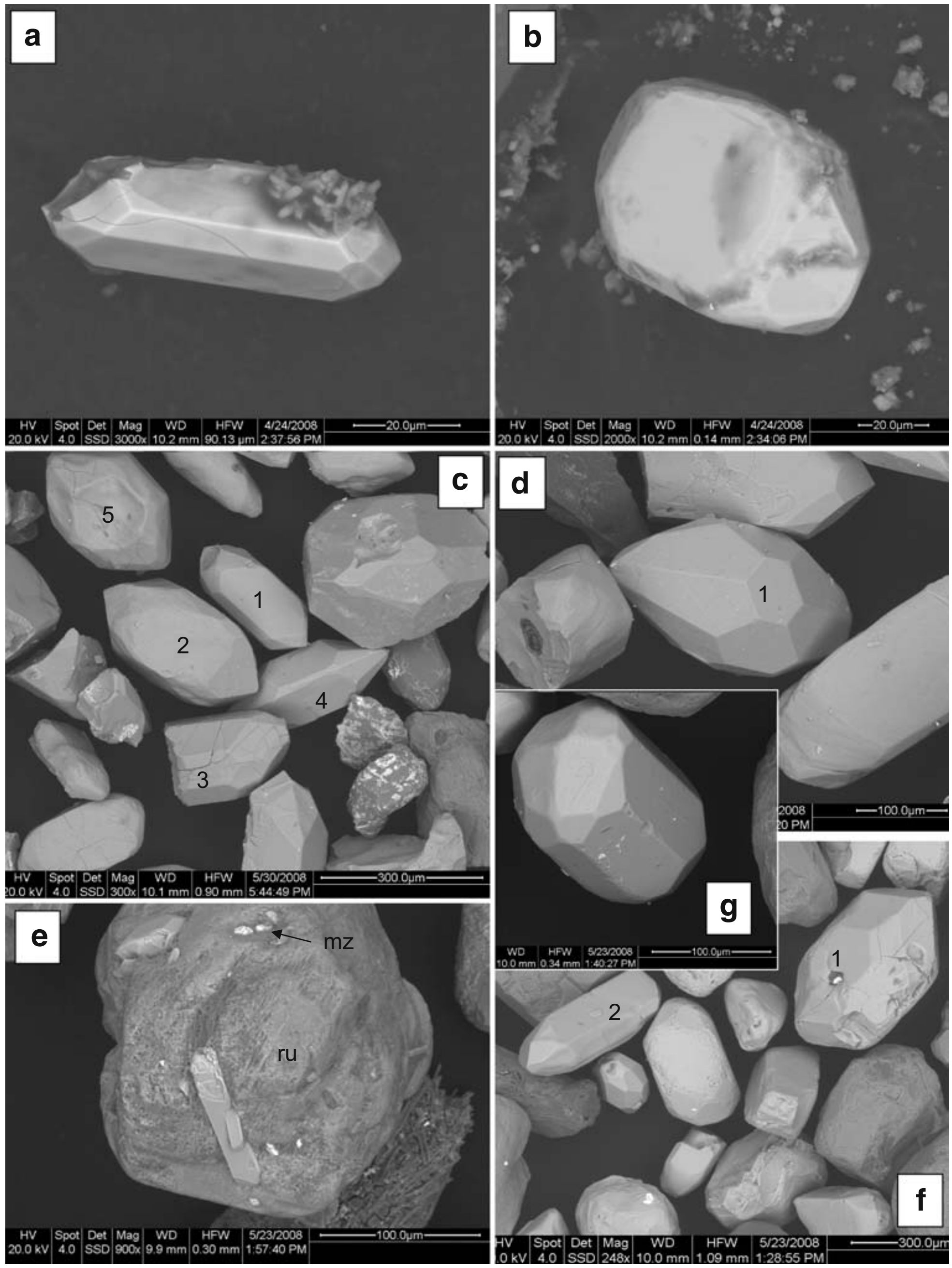


Fig. 5 Morphology of zircon grains from the “Donauplatin” placer in comparison with zircon morphology of adjacent placer deposits, **a** “Donauplatin”: type Ia prismatic zircon {100}≥{110} and {101}≥{211} **b** “Donauplatin”: type II platy zircon {100} >>{110} **c** Bayerischer Wald: prismatic to stubby zircon types (1) type Ia prismatic zircon {100}≥{110} and {101}≥{211}, (2) type Ib {100}≥{110} and {101}>{211}, (3) type Ic {100}={110} and {101}={211}, (4) type Id {100}>{110} and 211}, (5) type Ie {100}>{110} and {101}<{211} **d** Bayerischer Wald: bipyramidal stubby type III {100}={110} and {101}<<{211} **e** Naab drainage system: slender prismatic type IV {110} and {101} with growth zones. These elongated crystal can survive fluvial and alluvial transported as armored aggregates. Rutile is sheltering zircon as well as monazite (mz) **f** Type Naab drainage system (1) type V {100}<<{110} and {101}>{211}, (2) type Ia prismatic zircon {100}≥{110} and {101}≥{211} **g** Naab drainage system type If {100}≥{110} and {101}≤{211}

the “Donauplatin” placer (Tables 1 and 4). This is also true for the morphological parameters and the grain size. PGM have not been found so far in these placer deposits.

Silicates Garnet far less abundant in the heavy mineral suite than in the “Donauplatin” placer, belongs mainly to the almandine-grossularite s.s.s. Zircon, however, is very widespread and its morphology can be compared with zircon from the “Donauplatin” (Fig. 5c, d). Two principle types of zircon can be distinguished. Type I may be described as prismatic stubby, with subtypes Ib toIe differing only in the size of the prismatic faces of the tetragonal prism (Fig. 5c) (type Ia: {100}≥{110} and {101}≥{211}, type Ib: {100}≥{110} and {101}>{211}, type Ic {100}={110} and {101}={211}, type: Id {100}>{110} and 211}, type Ie: {100}>{110} and {101}<{211}. Type II is a bipyramidal stubby subtype showing the face relation {100} >>{110} and {101}<< {211} (Fig. 5d).

Phosphates Phosphate minerals are important in the heavy mineral suite of placers in the Bayerischer Wald, particularly monazite which is present in two different modifications: monazite I (La>Th), monazite IV (Th>La). Monazite I corresponds to the type-I monazite which was established

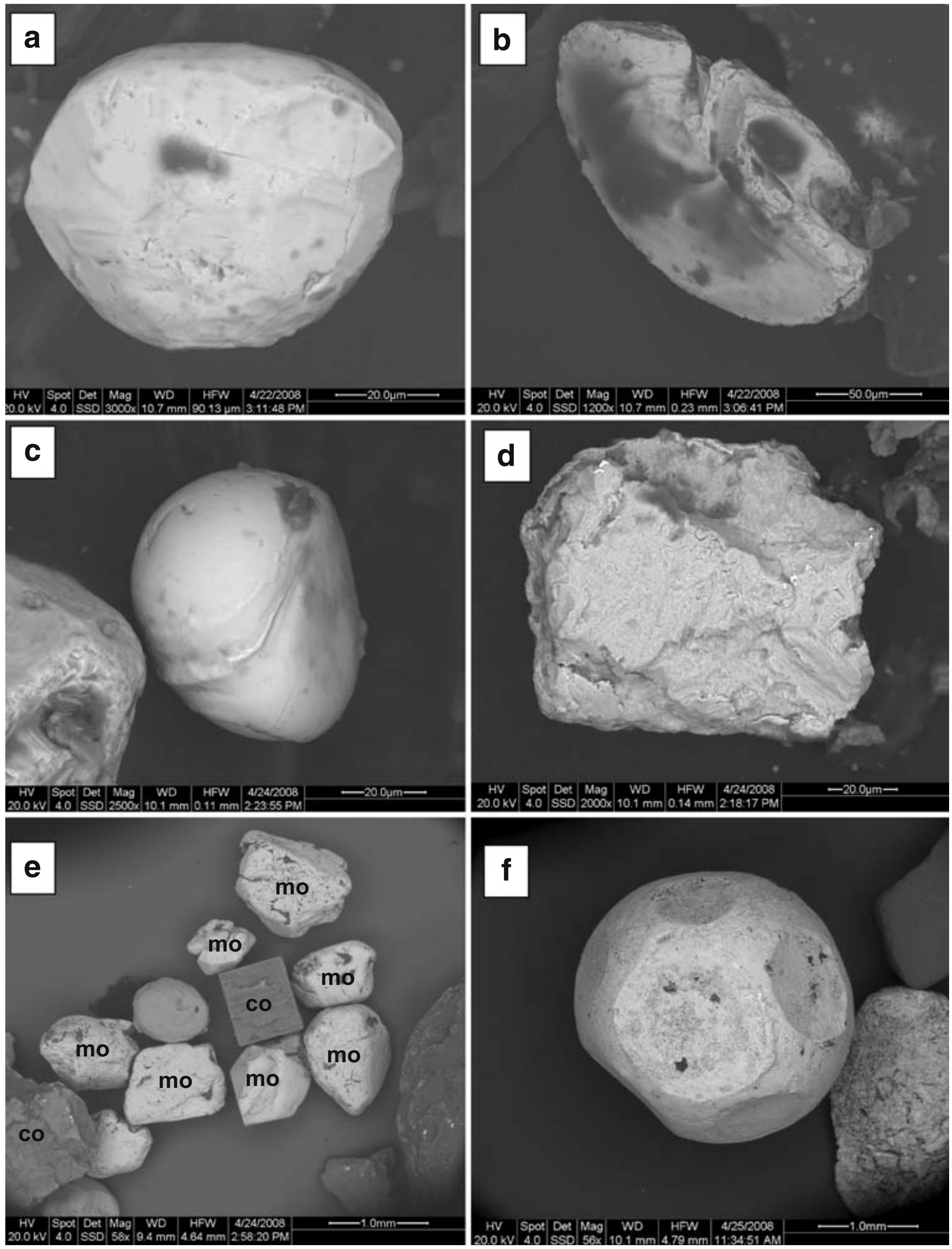


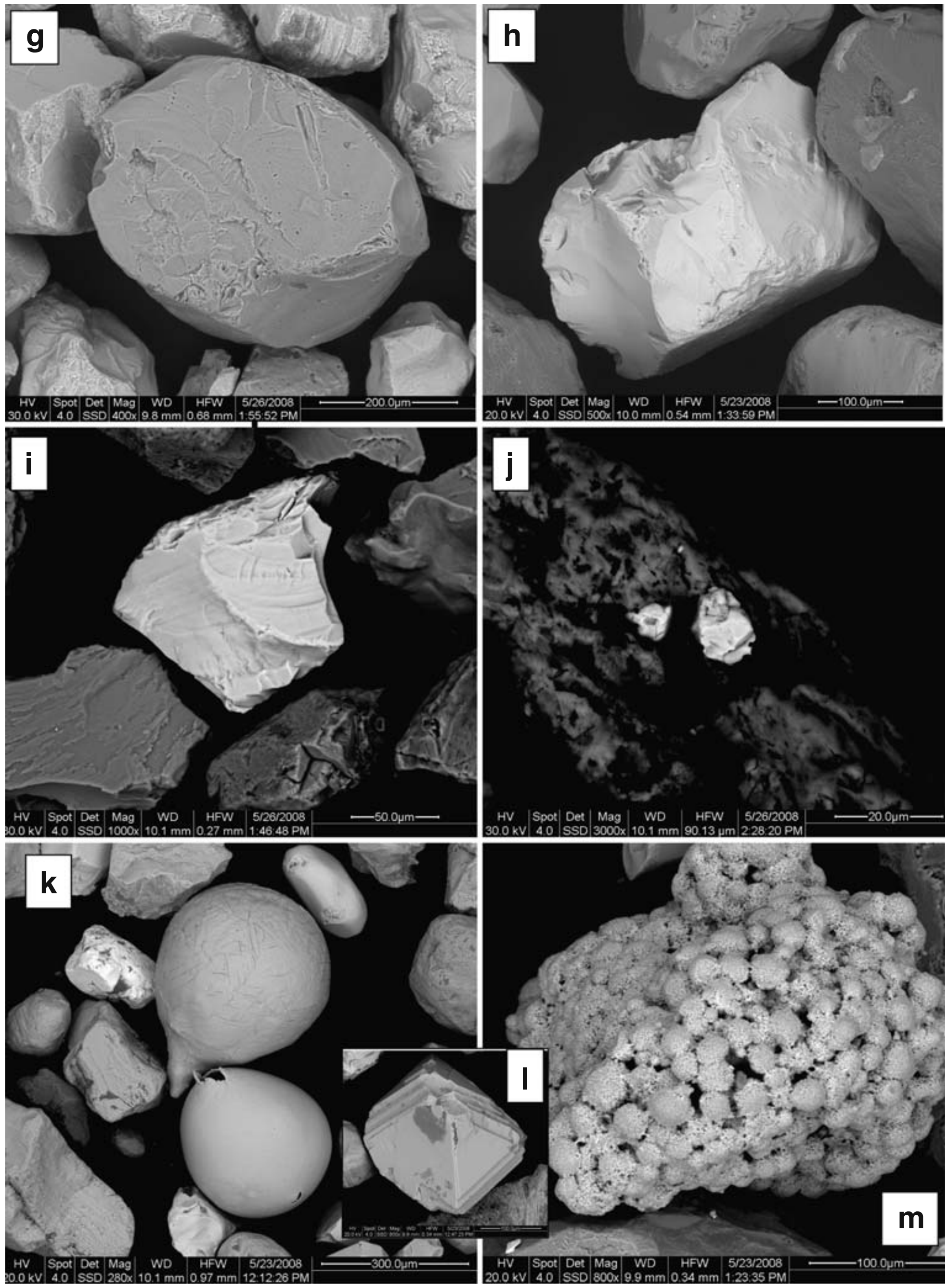
Fig. 6 Accessory minerals under the SEM **a** Rounded monazite type (La<Th) , "Donauplatin"**b** Cornish-type cassiterite transitional into "needle tin", "Donauplatin" **c** Chromium-iron melting drop, "Donauplatin" **d** Chromium-bearing magnetite, "Donauplatin" **e** Corundum (co) ("sapphire") amidst monazite (mo) showing different degrees of roundness, Bayerischer Wald **f** Rounded grains almost 100 % Pb with bounce marks, Bayerischer Wald **g** Subhedral almandine-spessartite garnet s.s.s. with beveled edges of the rhomb dodecahedral crystal, Naab River drainage system **h** Subhedral grains of cassiterite. Only relics of the tetragonal prism can be identified, Naab River drainage system **i** Anhedral grains of ferrocolumbite, Naab River drainage system **j** Uranian thorianite intergrown with monazite-(Ce), Naab River drainage system **k** Ferruginous melting drops, Naab River drainage system **l** (Inset) well-developed magnetite crystal intergrowth of various crystals facing the octahedron {111} **m** Framboidal pyrite, Naab River drainage system

in the heavy mineral assemblage of the "Donauplatin". It has a Th/La ratio of between 0.25 and 0.33 and a Th/Ce ratio of between 0.17 and 0.13. Unlike the "Donauplatin", monazite observed in the Bayerischer Wald is abnormally enriched in Th, with Th/La ratios of between 1.50 and 2.67 and Th/Ce ratios in the range 0.75 to 1.32, respectively. For better comparison with monazites from the "Donauplatin", this monazite has been given different code (monazite type IV). It is, in places, accompanied by xenotime and apatite.

Oxides Magnetite, rutile and ilmenite do not show any conspicuous morphological or compositional characteristics. Corundum crystals with deep blue color, however, attracted special attention (Fig. 6e). It is a turbid variety of blue corundum and its name "sapphire" has to be set between inverted commas to avoid any confusion with the gemological term used for the clear blue varieties of precious corundum (Hauner 1983).

Sulfides-sulfates-carbonates Sulfides are generally rare constituents in modern placer deposits and swiftly convert into minerals stable under oxidizing conditions. Galena has been altered along grain boundaries into cerussite and pyrite is intergrown with Fe-sulfate whose state of hydration cannot be determined. Both minerals are rare minerals of the placer mineral assemblage.

Fig. 6 (continued)



Metal and metal alloys High-antimony lead and high-tin-lead alloys were identified besides globules of almost pure lead (Table 5, Fig. 6f).

Mineralogical and chemical composition of the gold-bearing placer mineralization of the Naab River drainage system

Gold Gold grains were only sporadically encountered in heavy mineral sands from the Naab River drainage system and therefore any statistical treatment of this commodity is fraught with uncertainties. The particles are poor in Ag and of moderate sphericity (Table 6).

Silicates The composition of garnet from these placer deposits is as variegated as that of the “Donauplatin” placer, although grossularite- and spessartite-enriched garnet s.s.s. are much more common than in the Donau trunk river placers (Table 7). Spessartite-dominated garnet exhibits well-developed crystal morphology (Fig. 6g); normally, isometric garnet are encountered in these placers show poorly preserved faces and beveled edges. Implications of these observations habe been discussed by Dill (2007). Zircon is a common constituent and its grain population may be subdivided based on crystal morphology (Fig. 5e, f, g). Slender prisms of zircon are unlikely to be preserved in stream sediments because they are easily cracked during transport. In the Naab River drainage system, slender prismatic crystals of type IV {110} and {101} with remarkable growth zones escaped attrition and break-down on transport because they are armoured by rutile which also provided protection for associated zircon and monazite grains (Fig. 5e). Armored relics of "nigrine" and cassiterite play a significant role in the preservation of chemically and mechanically instable heavy minerals as was demonstrated for the nearby drainage system within the Hagendorf-Pleystein pegmatite province (Dill et al. 2006, 2007b). The term "nigrine" does not refer to a mineral *sensu stricto* approved by IMA, but it has been in use for a long time to denominate an intimately intergrown mineral aggregate of rutile and ilmenite hosting various mineral inclusions such as columbite-(Fe) (Ramdohr 1975, Dill et al. 2007b). Zircon type V displays the face arrangement $\{100\}<<\{110\}$ and $\{101\}>\{211\}$. While type Ia prismatic zircon with the arrangement of faces $\{100\}\geq\{110\}$ and $\{101\}\geq\{211\}$ has already been recorded from the Bayerischer Wald and the "Donauplatin", type I - $\{100\}\geq\{110\}$ and $\{101\}\leq\{211\}$ – is a composite of faces which so far have not been observed in the study areas in NE-Bavaria (Fig. 5g). In addition to ubiquitous zircon, sphene and tschermakitic hornblende have to be listed as accessory heavy minerals.

Phosphates Monazite prevails over xenotime, apatite and rhabdophane among the phosphatic heavy minerals. Type Ia-monazite has almost equal amounts of La and Th, whereas type Ib-monazite shows a preponderance of La relative to Th (Table 7).

Oxides Many oxides such as ilmenite, rutile, magnetite, goethite, cassiterite and corundum have already been mentioned in the section dealing with the heavy minerals from the Bayerischer Wald and "Donauplatin". As far as the morphology of grains is concerned there are remarkable differences between the various sampling sites. Cassiterite and corundum occur only as anhedral grains, while magnetite shows well-preserved octahedra {111} (Fig. 6i, l). Moreover, cassiterite contains notable amounts of Fe and Ti. A great variety of oxides have been found in the heavy mineral suite of the Naab River drainage system. Based on their Mg-and Al-contents spinel group minerals were classified as hercynite. Anhedral grains of columbite-group minerals were denominated as ferrocolumbite (columbite-(Fe)), owing to their element ratios of Fe>>Mn and Nb>>Ta (Fig. 6i). In one monazite grain, inclusions of uranian thorianite were spotted (Fig. 6j). Melting droplets and globules of iron oxide attract the examiner's attention under the SEM because of their perfect roundness (Fig. 6k).

Sulfides Aggregates of framboidal pyrite are quite common as is the case with anhedral aggregates of chalcopyrite (Fig. 6m).

Comparison of grain size and morphology of the "Donauplatin" with upstream placer mineralization

The grain size variation of heavy minerals and their host sands were plotted against the sphericity which was expressed by the ratio or particle length: width for the placer deposits under study (Fig. 7).

"Donauplatin" The sphericity of heavy mineral sands tend to decrease as grain size increases (Fig. 7a). The graph of the arenaceous host sediments may be taken as reference or used as a base line for the remaining graphs to show the evolution of the precious metal accumulation in the course of placer deposition. Gold undergoes a much stronger decrease in sphericity than the remaining detrital components with an overall dominance of isometric heavy minerals (garnet) and light minerals of poor cleavage (quartz). In the fluvial placer, there is a jump towards grains of lower sphericity beyond a grain size of 0.5 mm. The grains of PGM fall in a very narrow grain size interval below 0.3 mm but cover a rather wide spectrum of sphericity from well-rounded isometric grains of molybdenum-ruthenium-iridium-osmium alloys down to gold-palladium-copper alloys. Osmium-specialized alloys tend to have a higher sphericity value than iridium-dominated alloys. Platinum-bearing PGM take an intermediate position as regards sphericity but span a wider grain size interval.

Bayerischer Wald The graph of the host sand is not at variance with the graph known from the "Donauplatin", but the gold curve is. In the gold curve there is a break beyond a particle size of 0.5 mm but far less pronounced than in the "Donauplatin". There are fluctuations in the gold graph as in the equivalent graph of the "Donauplatin" but at a more moderate amplitude.

Naab River drainage system The baseline of the host sediment resembles the afore-mentioned curves (Fig. 7c). Gold, that is present in amounts far too small for any statistical treatment, reveals a similar trend to that in the x-y plot of "Donauplatin".

Discussion

Source of the Au placer minerals in the Bayerischer Wald

The fineness of gold, commonly expressed as fineness=Au/(Au+Ag)*1000, from the study area in the Bayerischer Wald

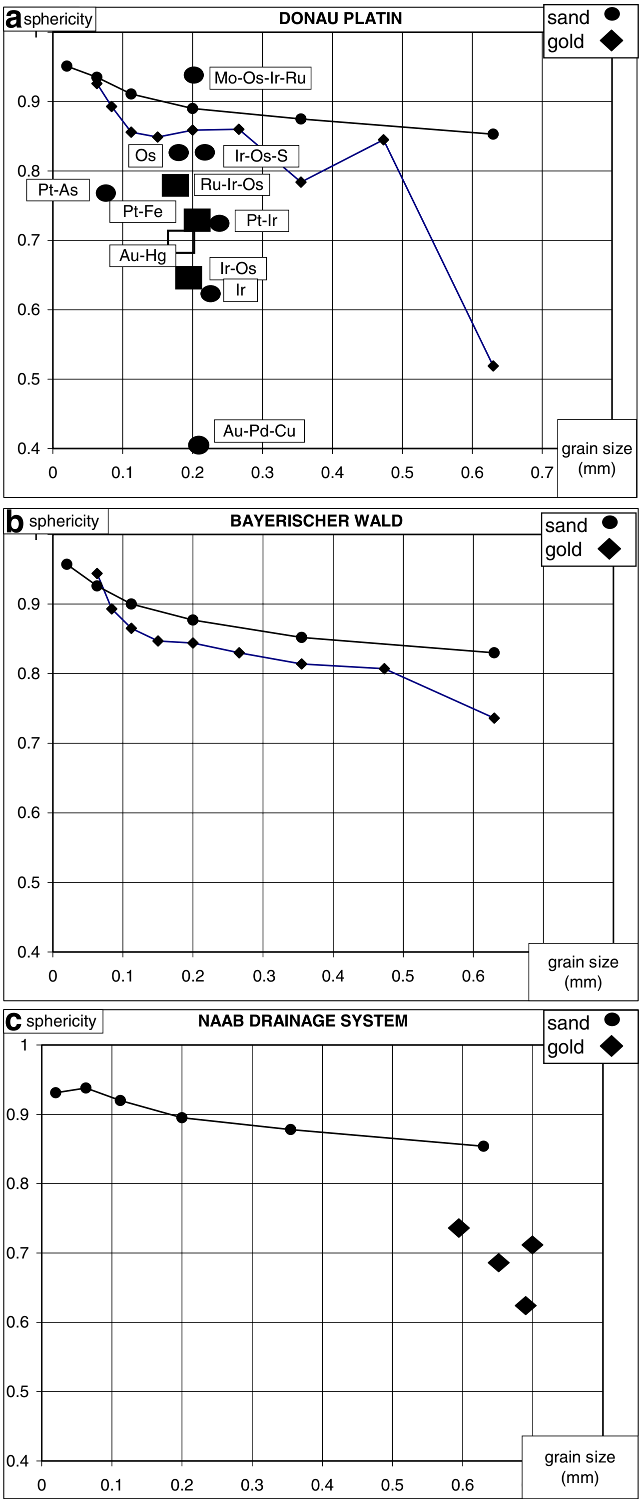


Fig. 7 Morphometry and grain size variation of fluvial PGM-Au ("Donauplatin") in comparison with alluvial Au placer mineralization and normal heavy mineral sands. Sphericity is given by the ratio length to width and the maximum value 1.0 is representative of the globe. Grain size is given in mm. Both parameters were measured with the CAMSIZER analytical device **a** fluvial PGE-Au placer mineralization ("Donauplatin") **b** alluvial fluvial Au placer mineralization (reworked lateritic gold from the SW edge of the Bayerischer Wald) **c** Au-bearing heavy mineral sand (reference heavy mineral sand from upstream of the study area)

is almost identical with the fineness of the "Donauplatin" but quite different from the fineness of gold placers in the NE Bavarian basement, which have a fineness around 940 and proximal placer deposits in the Swiss Alps and the Central Massif, France ranging from 785 to 983 (Dill 2008). In several studies, the chemical characteristics of placer gold have been used as an exploration guide in order to define the type of the potential source of gold and to constrain the position of the alluvial-fluvial gold system relative to its primary source (Knight et al. 1999, Dumula and Mortensen 2002, Townley et al. 2003). Why is the gold alloy in the Bayerischer Wald so poor in silver amidst a series of potential basement source rocks at proximal position? The answer to this question are the Neogene channel lag deposits, stretching in NW-SE direction through this part of the NE Bavarian Basement (Koch et al. 1997). Gravel, sand, clay and gold underwent strong re-deposition during the Neogene under (sub)tropical climatic conditions leading eventually to a lateritic blanket which capped the crystalline rocks of the NE Bavarian Basement. Santosh et al. (1992), who plotted the fineness of lateritic, placer and primary gold versus grain size were able to demonstrate that the lateritic gold and placer gold, both have a very high fineness significantly different from that of the nearby primary gold deposit in the crystalline basement rocks. Gold grains collected from the drainage system of Bavarian basement during this campaign is not primary but of secondary origin. As to the state of evolution and from the genetic point of view, this gold has to be called lateritic gold very similar to the well-known lateritic gold ore from Boddington, Western Australia (Morriss 1993, Anand and Butt 1998). With this in mind, the extreme fineness of gold in the "Donauplatin" placer is not a real surprise in view of the lateritic re-deposition on an ancient peneplain truncating the southern basement blocks of the Bayerischer Wald.

Source of the placer gangue minerals in the Bayerischer Wald

During provenance analysis of placer ore minerals emphasis was also placed on the gangue minerals which were deposited contemporaneously with the ore minerals. "Thrash" and "value" minerals belong to the same alluvial-fluvial drainage system which developed upstream from the same gravel catchment or source area. This approach may help to constrain the area but cannot be used to pinpoint properly the source rock lithology, where the debris came from. Placer mineral assemblages at a distal position relative to the source area underwent strong reworking and used to get deprived of Fe- and Mg-bearing heavy minerals due to their low resistance to weathering and attrition upon transport. This is especially true for those rock-forming minerals derived from (ultra)basic rocks which end up in stream sediments in the wake of erosion and pass through extensive milling and dissolution processes on alluvial-fluvial transport (Morton 1991, Dill 1998, Morton and Hallsworth 1999, Dill et al. 2006, 2007b).

The question, where gold and its associated minerals came from, can only be answered in this case by a closer look at the crystal morphology of zircon, a mineral that is unique among the heavy minerals due to its resistance to physical and chemical weathering. The morphology of detrital zircon grains in the placer deposits were compared with reference zircon types established by Pupin (1980, Tables 4 and 5). Type-I zircon points to source rocks which formed at temperatures between 750° and 800°C, while type III is indicative temperatures of formation around 850°C. Monazite is a heavy mineral ubiquitous in stream sediments of the brooks intersecting the NE-Bavarian basement. It lends support to the idea of using morphological criteria in constraining the source area of placer minerals (Kodymová and Kodym 1984, Schandl and Gorton 2004, Kusiaka et al. 2006). Kodymová and Kodym (1984) sampled a wide variety of magmatic, metamorphic and sedimentary rocks at 332 randomly distributed sites in the Bohemian Massif, in order to characterize the occurrence of heavy minerals. In the heavy mineral fraction the average monazite contents in crystalline rocks of the Bohemian Massif vary from trace amounts in pyroxene granulite up to 6.7 % in the granitoids of the Moldanubian Pluton (equivalent to 176 g/t of bulk rock). Detrital monazite can be derived either directly from the erosion of lithologies in which the mineral was precipitated, or from the erosion of pre-existing sedimentary deposits. Despite having a low hardness, monazite can readily be recycled even from weakly cemented siliciclastic sediments. According to the above authors, monazite derived from magmatic to metamorphic source rocks (Type I). Metamorphic monazite paleoplacer deposits are confined to certain layers in metamorphic rocks along the edge of the Bodenmais Kieslager belt and correlated with type-II monazite (Teuscher and Weinelt 1972, Dill 1990). Strunz (1961, 1962) recorded Th contents of 1500 to 2500 ppm and U contents in the range 100 to 150 ppm from that area known for its monazite paleoplacers in the Bayerischer Wald. These REE phosphates in the paleoplacers may be traced back to high pressure metamorphic rocks as the ultimate source according to the results of Finger and Krenn (2007). Based on microstructural and compositional criteria, three generations of monazite have been identified by the above authors in a peraluminous, garnet-rich, high-pressure metamorphic rock from the Bohemian Massif. The first monazite generation (M1) formed probably on the prograde part of the clockwise PT loop, a second generation (M2) during the high-pressure stage (26±3 kbar and 830±30°C) and a third generation (M3) during subsequent near-isothermal decompression of the rock down to 8±2 kbar.

Unusual blue corundum (“sapphire”) has been derived from magmatic source rocks. Igneous rocks bearing corundum were described from the intrusive contact of pegmatites with the wall rocks (Sperling, 1990). Zircon (hyacinth) in placer gravels along with precious corundum in Myanmar and Cambodia have been derived from deeply weathered alkali basalts (Schumann 1997, Gübelin and Erni 2000). Simonet et al. (2004) studied the unique magmatic gem-corundum deposit Dusi, Kenya, which is bound to monzonitic intrusive rocks. In addition to corundum, this mineralization also contains zircon of type S 11 *sensu* Pupin (1980), indicating a formation temperature of approximately 750°C. Magnetite, rutile, xenotime and apatite associated with zircon are of no relevance to the characterization of the source area. Galena and pyrite may be traced back to hydrothermal mineral deposits which sporadically occur in the southern part of the Bavarian basement. Lead and lead alloys are artifacts such as relics of ammunition and remnants of rechargeable batteries, movable types and solder.

Source of the placer minerals in the Naab River drainage system

The gold content of the samples studied from the Naab River drainage system is too low to justify any lengthy discussion on whether it might have contributed to the gold content of the “Donauplatin” placer or not. Based on the chemical composition and the information gathered by Dill (2008) the source may be described as “orogenic gold” *sensu* Groves et al. (1998).

Garnet in the stream sediments is chemically variable and it may be attributed to various types of host rocks spanning the whole range from basic magmatic rocks through pegmatites and paragneisses to calc-silicate rocks (Tables 7

Table 4 Mineralogical and chemical composition of gold placer mineralization of the Bayerischer Wald

Mineral	Crystal system	Hardness	Cleavage	Mean sphericity	Mean size	Shape class	AU	Provenace
Gold	isometric - hexoctahedral	3	none	0.842	260	subangular to angular	+	Lateritic gold

Mineralogical and chemical composition of the gold grains

Table 5 Mineralogical and chemical composition of gold placer mineralization of the Bayerischer Wald

Associated minerals	Intergrowth and varieties	Provenance
Garnet	Grossularite-almandine s.s.s.	Calcsilicate fels
Zircon	Type Ia {100}≥{110} and {101}≥{211}	Type Ia: 750°C igneous
	Type Ib {100}≥{110} and {101}>{211}	Type Ib: 750°C to 800°C HP metamorphics
	Type Ic {100}={110} and {101}={211}	Type Ic: 750°C HP metamorphics
	Type Id {100}>{110} and 211}	Type Id: 800°C HP metamorphics
	Type Ie {100}>{110} and {101}<{211}	Type Ie: 800°C HP metamorphics
	Type III {100}={110} and {101}<< {211}	Type III: 750°C igneous
Monazite- (Ce)	Type I: monazite-(La-Th)	Type: I: igneous and metamorphic hp metamorphics
	Type IV: monazite-(Th-La) (very rich in Th)	Type IV: meta-palaoeplacers recycled from hp metamorphics
Xenotime		No source rock indication
Apatite		No source rock indication
Corundum	"sapphire"	Contact zone of intrusive rocks / pegmatites (approx. 750°C)
Magnetite		No source rock indication
Ilmenite		No source rock indication
Rutile		No source rock indication
Galena		Hydrothermal mineralization
Pyrite		Hydrothermal mineralization
Cerussite		Supergene alteration of galena
Fe sulfate		Supergene alteration of pyrite
Lead-antimony alloys	Pb 13 % Sb 87 %	Rechargeable batteries or movable types
Lead-tin alloy	Sn 87 % Pb 13 %	Solder
Lead	Pb 100 %	Ammunition

Minerals associated with the Au minerals. Intergrowth and varieties denote solid solution series (s.s.s.) of minerals based on SEM-EDX analysis, morphological differences and intergrowth of heavy minerals with light minerals

and 7). Sphene and hornblende associated with garnet furnish evidence that it originated from calc-silicates and metamorphic basic magmatic rocks. Type-I zircons in the stream sediments are typical of source rocks which formed between 750° to 800°C, while types IV and V which prevail over type I developed at a significantly lower temperature around 600° and 650°C. The phosphate assemblage in the stream sediments indicates a lower temperature regime in the source rock area than in the southern Bayerischer Wald, and it is most likely of hydrothermal origin. Ferrocolumbite, bipyramidal grains of cassiterite and U-Th oxides leave no doubt as to a pegmatitic derivation of these heavy minerals, what is also in agreement with the regional geology in the catchment area of the Naab river drainage system. It is, however, difficult to tighten a specific pegmatite that might have been the source for these heavy minerals due to the widespread occurrence of pegmatites in this part of the NE-Bavarian basement (Strunz et al. 1975). REE phosphates predate U-Th oxides within the source pegmatite and are connected with Ti-(Fe) oxides postdating them. Ilmenite and rutile are seldom present as single crystals but occur intergrown with each other in mineral aggregates called "nigrine". They are clear-cut mineralogical markers for the marginal facies of pegmatites and quartzose shear zones (Dill et al. 2007b). Corundum in the heavy mineral spectrum is of sub-gem quality. Spinel, which is associated with corundum in the stream sediments, is interpreted to have been derived from corundum-hercynite fels, a highly desilicified rock of metabauxitic origin. Well-crystallized octahedra of magnetite may be traced back to the meta(ultrabasic) rock of the

Table 6 Mineralogical and chemical composition of placer mineralization of the Naab River drainage system with little gold

Mineral	Crystal System	Hardness	Cleavage	Mean sphericity	Mean size	Shape class	Au	Provenance
Gold	isometric - hexoctahedral	3	none	0.700	650	subangular	+	Orogenic gold deposit

Mineralogical and chemical composition of the gold grains

Table 7 Mineralogical and chemical composition of placer mineralization of the Naab River drainage system with little gold

Associated minerals	Intergrowth and varieties	Provenance
Garnet	Pyrope-almandine-grossularite s.s.s.	Basic igneous rocks
	Almandine-enriched	Paragneiss
	Almandine- spessartite s.s.s	Pegmatite
	Almandine-pyrope s.s.s.	Basic igneous rocks
	Grossularite-almandine s.s.s.	Calcsilicate fels
	Grossularite-enriched.	Calcsilicate fels
Zircon	Type Ia: {100}≥{110} and {101}≥{211}	Type Ia: 750°C
	Type If: {100}≥{110} and {101}≤{211}	Type If: 750°C to 800°C
	Type IV: {110} and {101}	Type IV: 600°C
	Type V: {100}<<{110} and {101}>{211}	Type V: 650°C
Sphene		Calcsilicate fels and amphibolite
Amphibole	Tschermakitic hornblende	Metamorphic basic igneous rocks
Monazit (Ce-)	Type Ia: monazite-(La-Th)	Type: Ia: igneous (or metamorphic)
	Type Ib: monazite-(La≥Th)	Type: Ib: hydrothermal (?)
Rhabdophane		Hydrothermal alteration of monazite
Xenotime-(Y)		No source rock indication
Apatite		No source rock indication
Columbite group	Fe>>Mn, Nb>>Ta ferrocolumbite	Pegmatite
Spinel group	Hercynite	Corundum-hercynite fels
Uranium-thorium oxide	Uranian throrianite	Pegmatite
Cassiterite	Fe-Ti bearing cassiterite	Pegmatite
Corundum	Anhedral	Corundum-hercynite fels
Magnetite	{111}	No source rock indication (magnetite fels metabasic rocks)
Iron oxides	Melting drops and bubbles	Smelter
Ilmenite	Mn-free ilmenite	Pegmatite to shear zones –see “nigrine”
	Pyrophanite-ilmenite s.s.s.	
Rutile		Pegmatite to shear zones–see “nigrine”
Pyrite	Framboidal pyrite	Urnaab River drainage system (brown coal)
Chalcopyrite		Urnaab River drainage system (brown coal)

Minerals associated with the Au minerals. Intergrowth and varieties denote solid solution series (s.s.s.) of minerals, morphological differences and intergrowth of heavy minerals with light minerals. Composition of garnet is based on SEM-EDX analysis

Erbendorf Complex which is located upstream of the sampling site (Dill 1985). Framboidal pyrite and aggregates of chalcopyrite would not have survived any long transport in the Naab River drainage system and have certainly been incorporated as rip-up clasts from the lignite-bearing Neogene Naab River system underneath, draining into the Alpine foreland basin during the stage of the Neogene upper Freshwater Molasse (Dill et al. 1993).

Source of the Au-PGE placer minerals in the “Donauplatin”

Based upon the previous discussion on gold, there is only one plausible explanation for the extreme fineness of gold observed in the “Donauplatin” placer. Gold has been derived from the nearby “Bayerischer Wald”. Gold particles present in the Danube were re-deposited from “secondary” lateritic gold, whose primary source may be defined with regard to its origin as orogenic gold but cannot be sited precisely in the Bohemian Massif.

Gold-palladium-copper compounds were described from the central parts of the Bohemian Massif by Malec and Veselovsky (1985) and form the Koryak–Kamchatka platinum-bearing belt of Alaskan-type intrusions in eastern Russia by Tolstykh et al. (2000). Palladium has been attributed by these authors to the late-magmatic hydrothermal-metasomatic stage. The placer mineral assemblage observed in the NE - Bavarian sampling sites is very much different from that of the Koryak–Kamchatka platinum-bearing belt of Alaskan-type intrusions so that this process is not likely to have contributed to the build up of our detrital PGE mineralization. Another mineralization process leading to Pd-bearing gold has been recorded from hematite veins in the banded iron formation (BIF) of the Itabira mining district, Brazil, by Olivo et al. (1995) who correlated the formation of Pd-bearing gold with the climax of the regional metamorphism at 600°C and the stage of most intensive shearing and thrust faulting. Native palladium is present only under oxidizing conditions corresponding to the stability field of hematite (Cabral and Lehmann 2003). In conclusion, Pd-bearing gold occurs in a rather narrow stability field under oxidizing conditions in shallow hydrothermal systems devoid of or poor in sulfur. A few lithologies and structural units in the nearby NE-Bavarian basement comply with the thermo-dynamic conditions recorded from Brazil. The metallogenetic setting taken for reference may be correlated in the NE- Bavarian Basement with regionally metamorphic processes that reached their peak temperature at about 600°C. A rise in temperature was accompanied by strong shearing and folding around the Great Bavarian Quartz Lode (“Pfahl”) which extends in NW-SE direction through the Bayerischer Wald (Fig. 1c, d). We hypothesize that primary gold-palladium-copper alloys developed synmetamorphically in a sulfur-deficient environment of formation.

The PGM assemblage of the “Donauplatin” placer was compared with various PGM assemblages found within the clastic apron around primary PGE deposits (Fig. 8). Mineral assemblages dominated by iridium-osmium and ruthenium-iridium-osmium alloys were recorded mainly from placer deposits surrounding ophiolite-related PGE deposits in the Chindwin Basin, Burma/Myanmar and from the Aikor River in Papua New Guinea (Hagen et al. 1990, Cabri et al. 1996, Weiser and Bachmann 1999, Weiser 2002). Some of our data along the Os-Ir tieline fall in the miscibility gap of the Os-Ir-Ru system (Fig. 8). These data were explained by high temperatures of formation or may be due to the deviation from the Pt-free system (Rudman 1967, Weiser and Bachmann 1999). Osmium-iridium alloys with negligible amounts of Ru are also described from PGMs in the Guli ultramafic massif in Northern Siberia or zoned-type deposits (also referred to as Aldan type, Uralian-type or Alaskan-type, Malitch et al. 2002). This type of source rocks may be ruled out in the study area for geodynamic reasons (Propach and Pfeiffer, 1998). Another option in the provenance analysis might be pervasive chemical weathering and erosion that penetrated deeply into the basement and led to the complete eradication of the PGE source rocks such as shown by an investigation of Johan et al. (1990) for PGM from the Durance River alluvium, France, where the primary source of an Alaskan-type intrusion is highly speculative and was obviously completely eroded.

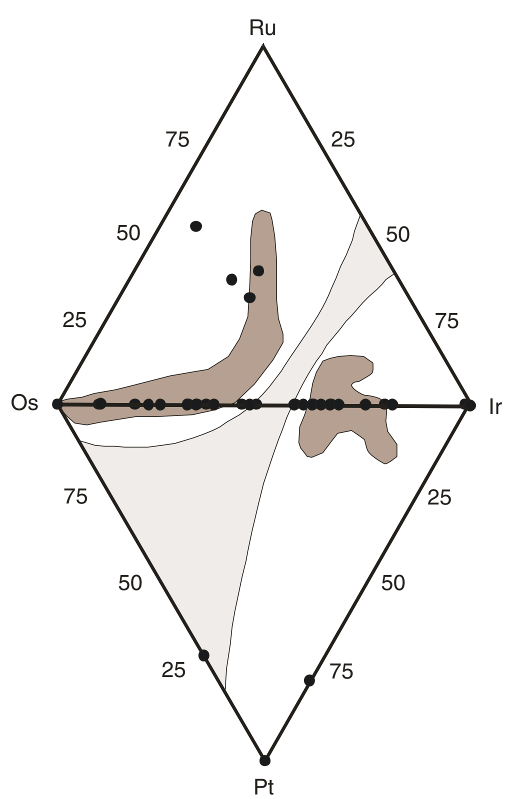


Fig. 8 Correlation of the “Donauplatin” (black dots) with reference data compiled by *Cabri* et al. (1996) in the double-triangular plot Ru-Pt-Ir-Os. Bright shaded area: miscibility gap, dark shaded areas: reference data arrays

Platinum-iron alloys are also known from ophiolite-related PGE deposits and held to be typical of the New Caledonian subtype (Augé and Legendre 1994, Augé et al. 1995). A mineral closely resembling the unknown Ir-Os sulfide was described from chromitite from the Osthammeren ultramafic tectonite body (Nilsson 1990). Iridium-bearing platinum was also recorded from Alaskan-type deposits. Sperrylite is recorded from a great variety of primary PGE deposits and thus gains little significance as a marker mineral in the current study (Weiser 2002).

Molybdenum-ruthenium-iridium-osmium alloys have not yet been reported from primary or secondary PGE deposits so far. An unnamed Mo-bearing PGE alloy (Fig. 4b), coded IMA 2007-029, was only described from the Allende meteorite, Chiuahaha, Mexico

Magmatic PGE mineralizations were described from the Bohemian Massif, albeit all of them are currently subeconomic. Nickel-copper ore mineralization in basic and ultrabasic rocks of the Ransko Massif, Czech Republic, in gabbroic dikes at Kunratica and Rožany and Svitavy is characterized by Pd-Bi-Te-Pt-As minerals associated with a variegated spectrum of non-PGE sulfides (Pašava et al. 2003). This type of source rock hardly qualifies as source of the “Donauplatin” even if a supergene differentiation of PGM in the fluvial drainage system may be envisaged. Hydrothermal deposits such as at Předbořice, Czech Republic, show Se-enriched Ni-Cu mineralization with merenskyite and do not qualify as source of the “Donauplatin” either (Johan 1989). The low-grade-large-tonnage deposits or PGM-bearing black shales may be excluded as a PGE source due to the size and type of PGM. It has to be noted that the placer deposits of the alluvial pyrope deposits Vestřev in the northeastern Trutnov basin are quite similar to the "Donauplatin" as far as their composition is concerned and contain besides pyrope-dominated garnet s.s.s. mainly Pt-Fe and Os-Ir alloys. Similar to the "Donauplatin" placers the provenance area for these PGM is unknown (Malec 1997).

A comparison of the mineral assemblages of the PGM-bearing podiform chromitites in the Austroalpine Crystalline basement east of the Tauern Window with the " Donauplatin" shows a great affinity between these PGE deposits and the studied PGE-Au placer deposits (Malitch et al. 2001, Malitch et al. 2003a, 2003b). The banded chromitites have a pronounced enrichment of Pt and Pd relative to the more refractory platinum-group elements Os, Ir and Ru. The mineralization is, however, more variegated than the "Donauplatin", a fact which can be explained by differentiation on transport. Kraubath and Hochgrössen, Austria, are located in the Speik Complex in the Austroalpine basement units, which today form part of the catchment area of the Mur-Drau fluvial drainage system. These tributaries run into the Donau trunk river downstream of the placer mineralization under study in SE Germany.

About 50 km NNE of the sampling site, metabasic and ultrabasic rocks of the Tepla Barrandian unit are exposed within the Bayerischer Wald (Propach and Pfeiffer 1998). It has been re-interpreted by the authors as a dismembered ophiolitic sequence but has not yet been tested positively for PGE mineralizations.

Source of the placer gangue minerals in the "Donauplatin"

Garnet in the stream sediments of the "Donauplatin" placer could have been derived from paragneisses (metapelitic rocks), calc-silicate rocks, skarnoid rocks and meta(ultra) basic igneous rocks, rocks which are all exposed at the northern edge of the Bayerischer Wald, where metamorphic rocks of the Moldanubian zone are in contact with rocks of the Tepla Barrandian unit (Propach and Pfeiffer 1998). In accordance with data published by Pupin (1980), the morphological types of zircon point to a temperature regime between 750°C and 800°C for the source rocks of zircon.

Monazite may be subdivided into three types: (1) Type I: monazite-(Th), (2) Type II: monazite-(Th-U), (3) Type III: monazite-(U-Th). Type I has already been discussed with regards to its derivation. Based upon the results obtained by Finger and Krenn (2007) and Schandl and Gorton (2004), type II and III may be correlated with HP metamorphic rocks and hydrothermal processes, respectively. Rare cassiterite suggests a medium to low-temperature granite-related Sn mineralization not far from the depocentre in the Bayerischer Wald. These finds of cassiterite demonstrate that the Moldanubian Zone of the Central European Variscides is also host of Sn mineralization albeit of lesser importance than the Saxothuringian zone. Other minerals are only of limited use as provenance indicators. It is a tantalizing idea to use the Cr-bearing compounds, e.g. Fe-Cr spinels, in the stream sediments to trace back the PGM to ophiolite-hosted podiform chromitites. However morphological parameters of these Cr-Fe compounds rather support an anthropogenic origin of these compounds. A human impact is also seen in the gold-amalgam in the "Donauplatin" placer which is due to gold beneficiation processes upstream of the sampling sites (Table 1).

There is convincing evidence that the gangue minerals in the "Donauplatin" placer have been derived from the Moldanubian basement rocks. Based upon the present data, any significant input from the northern Saxothuringian Zone via the Naab River tributaries can be discarded for the fluvial placers under study.

Formation of the "Donauplatin" and its upstream placer mineralizations

In the grain size vs. sphericity plots, the "Donauplatin" shows three different trends, which may shed some light on the mode of formation of these fluvial PGE-Au placer deposits (Fig. 7). The "baseline", provided by the host sediments reflects the normal "water-borne" trend from high-sphericity values at lower grain size intervals to lower sphericity at higher grain size intervals. This also applies for the Neogene channel lag deposits of the paleodrainage system in the Bayerischer Wald as well as for the Holocene floodplain sediments of the Donau River and its tributaries. The "gold trends" in the various environments of deposition are similar up to the grain size interval 0.5 mm with two "lows" between 0.1 to 0.2 mm and 0.3 to 0.5 mm in both sphericity graphs which give evidence of a common source but different impacts on the gold particles. Gold is a rather malleable metal, which becomes more and more milled on transport. Not surprisingly, the sphericity contrasts become more and more striking from alluvial to fluvial. The gold data of the Naab River drainage system, although not suitable for an overall statistical treatment, show a sharp decline in sphericity on transport. Morphometric and granulometric assessments are of assistance in discriminating between proximal/alluvial-fluvial and distal/fluvial gold placers. PGE do not follow these Au trends and fall in a narrow grain size interval that can be inherited from the primary deposits. All PGM have a Mohs hardness sometimes more than twice as high as gold. Some have a perfect cleavage which has obviously no significance to the shaping of PGM on transport (Table 1). We interpret these variations in sphericity as inherited and consider PGM as less vulnerable to attrition during alluvial-fluvial transport than gold. The contrasting sphericities of gold-palladium-copper alloys and molybdenum-ruthenium-iridium-osmium alloys are due to source variation (Table 1).

Morphoclimatic setting and placer development

The fluvial system of the Naab River drainage system and its predecessor called "Urnaab" (ancient Naab River System) may be described as a meandering river system in its lower reaches with clay, siltic fine sand and dirty high ash coals filling the wide channel system (Dill 1991). Measured on an annual basis, the Naab river system discharges approximately 40,000 m^3 of bed load from the NE Bavarian basement into its trunk river the Donau, while during the same period of time the southern tributaries of the River Donau carry a bed load of approximately 530,000 m^3 from the Alps into the Donau (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz and Ministerium für Umwelt und Verkehr Baden-Württemberg 2006). Altitudes between 600 and 1000 m a.m.s.l. in the catchment area of the NE Bavarian Basement compared with heights of more than 2000 m in the northern part of the Alps account for these river discharges. The alluvial-fluvial drainage system developed within a temperate climatic zone characterized by an annual precipitation of 1030 mm and temperatures in the range −1°C to 20°C. The Au-PGE placer evolution in the tributaries as well as the main river is unrelated to the modern morphoclimatic processes during the post-glacial period. The major impact lies within the Neogene morphological processes and the variation of source area.

Conclusions

The "Donauplatin" is a distal fluvial PGE-Au placer which by means of morphometric and granulometric data may be compared with other fluvial placers in central Europe and differs significantly from proximal alluvial-fluvial placers. The major proportion of the PGM assemblage has been derived from ultrabasic magmatic rocks, most probably from still unknown ophiolite-related mineralization in the Tepla Barrandian unit or ultrabasic rocks intercalated into metamorphic rocks of the Moldanunbian Zone of the nearby Bayerischer Wald. The Moldanubian basement rocks *sensu stricto*, have not contributed to the PGE budget in the "Donauplatin". They have only contributed to the gold content and the Au-Pd compounds in the "Donauplatin" placer. A significant input from the Saxothuringian zone may be ruled out for gold, PGE and much of the gangue minerals based on the heavy mineral analysis of gangue and ore minerals. Extraterrestrial processes such as the Nördlingen Ries impact may have had a minor share in the PGE budget by delivering molybdenum-ruthenium-iridium-osmium alloys and iridium.

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