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Integration of detrital gold microchemistry, heavy mineral distribution and sediment geochemistry to clarify regional metallogeny in glaciated terrains: application in the Caledonides of southeast Ireland

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Integration of detrital gold microchemistry, heavy mineral distribution and sediment geochemistry to clarify regional metallogeny in glaciated terrains: application in the Caledonides of southeast Ireland

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Abstract

Regional exploration for rare and precious metal enrichment traditionally uses multi-element geochemical analysis of the fines (<150 µm) fraction of stream sediments, however these data can be misleading in glaciated regions with complex geology. Here we compare the spatial distributions of data from sediment fines with distributions of heavy mineral concentrates including detrital gold in the same region. Gold grains are characterized according to abundance and morphology, plus a 'microchemical signature' from the combination of alloy analysis and systematic identification of mineral inclusions revealed in polished sections. These inclusions survive indefinitely and are indicative of hypogene mineralogy, whereas the metal loadings of fines may be affected by weathering or anthropogenic activity. All three approaches are mutually supportive: sediment fines analyses provide a basis for more labour-intensive targeted gold grain studies, which in turn highlight specific gold-element associations useful for interpretation of geochemical datasets. Spatial distributions of resistate heavy mineral suites constrain the directions and extents of glacial transport which facilitates more confident interpretations of placer-lode relationships from gold grain studies.

Characterisation of 2160 gold grains from 40 localities in the auriferous region of southeast Ireland provided a clear indication of proximity of gold to source, and identified gold derived from different episodes of mineralization. A distinction is apparent between gold in the south of the region (Wexford), likely derived from widespread stratabound Au-As-Fe-S mineralization, and that in the north (Wicklow) where the historical placer mining district of the Goldmines River yielded gold with inclusions exhibiting a distinctive Pb-Bi-As association. The Goldmines River placers formed by the efficient accumulation and preservation of detrital gold derived from several discrete intra-valley sources. We recommend that a combination of classical stream sediment geochemistry, heavy mineral analysis, and gold grain studies is used more widely to provide additional insights on the location and nature of gold mineralization and regional metallogeny in regions of poor exposure and complex geology.

Key words: Placer gold, detrital gold, heavy minerals, stream sediment geochemistry, glaciated terrain, metallogeny, orogenic gold, microchemical characterization, Caledonides

Introduction

Stream sediment geochemical datasets are traditionally applied during mineral exploration to identify vectors to mineralized areas (e.g. McLenaghan and Cabri, 2011). Two approaches are commonly employed in tandem, one centering on the chemical composition of a fine fraction (typically <150 µm) and the other on the chemistry or mineralogy of a panned concentrate. The 'fines' fraction is often preferred in regional studies as it can identify broad anomalies at spacing of one sample per a few square kilometres. The panned concentrate (hereafter 'heavy mineral concentrate'), may be useful in directly identifying ore minerals whose longevity in the surface environment is limited, but which may be present close to their bedrock source. Regional geochemical studies using these techniques commonly contribute to initial evaluations of the prospectivity of an area of interest and may be undertaken by Government agencies whose aim is to stimulate further, focussed exploration.

Southeast Ireland has a maritime climate and a well-developed drainage network due to the hilly topography. Mineral exploration in the region has benefitted from an extensive regional stream sampling and geochemical analysis program ('Tellus') which has generated high resolution (1 per 4 km^2) data sets mostly in the counties of Wicklow and Wexford (Fig. 1) (Knights and Heath, 2016). Regional lithologies comprise an assemblage of Palaeozoic metasedimentary, volcanic and igneous intrusive rocks that were deformed in the Late Ordovician – Early Silurian during the Caledonian orogeny. The region is of interest because of Kuroko-style volcanogenic massive sulphide mineralization at Avoca in County Wicklow that has yielded around 100,000 tonnes of copper metal (Tietzsch-Tyler et al., 1994) and because of historical placer gold extraction. In 1795, the Ballinvally area ~7 km south of the Avoca mines was the scene of Ireland's only historical 'gold rush' for placer resources. It has been estimated (Reeves, 1971) that up to 300 kg of placer gold was recovered from gravels in the Ballinvally and Monaglogh River valleys (Fig. 1) and surrounding area. Some of the gold was very coarse-grained, the largest mass being the 'Wicklow nugget' weighing 22 ounces (682 g) which became the property of George III. A replica of this nugget is in the Natural History Museum, London. However, despite intense exploration during the following century, the bedrock source or sources were not identified. The Ballinvally and Monaglogh Rivers collectively became known as 'Goldmines River'. Modern exploration since the 1980s has extended the area of interest to the south and southwest, and several areas prospective for gold mineralization have been identified by mineral industry exploration using soil geochemistry, geophysical surveys, trenching and drilling (Fig. 2). Current exploration company interest in the region is at least in part a consequence of the Tellus data releases.

Two major challenges face such exploration programmes; firstly the paucity of bedrock exposure typical of areas subjected to Quaternary glaciation, and secondly the complex geology comprising metasedimentary and metavolcanic rocks and igneous intrusions which provide the possibility of different styles of gold mineralization. In common with many orogenic belts worldwide, the abundance and distribution of placer gold in SE Ireland provides the most powerful indicator of local mineralization, even though the location(s) of the source remain unclear. Analyses of gold grain alloy chemistry, combined with the mineralogy of opaque mineral inclusions revealed in polished sections through grains, generates a 'microchemical signature' which has been used to advantage in such scenarios to distinguish different styles of mineralization from which the detrital gold is derived (e.g. Chapman et al., 2017). This approach has been used to illuminate local variation in orogenic gold signatures (Chapman et al., 2010a,b; Chapman and Mortensen, 2016) and to infer spatial variation in mineralization within intensely glaciated areas of the British Caledonides where bedrock exposure is scarce (Leake et al., 1998, Chapman et al. 2000a). This methodology appears ideally suited to generating new insights into the metallogeny of the study area.

This study considers data derived from three approaches to geochemical exploration which utilise material collected from fluvial environments; the recently published Tellus data set, and two new databases describing the mineralogy of heavy mineral concentrates and detrital gold.

Geological background

Geology and tectonic setting

Southeast Ireland comprises a NE-SW oriented belt of Cambrian and Ordovician sedimentary and volcanic rocks (Fig. 1) that were tectonically deformed and metamorphosed during the Lower Palaeozoic. Cambrian turbidites outcrop to the SE and NW with Ordovician basinal strata in a central belt. In the lower Ordovician, thick laminated mudstones were deposited: the striped appearance of these gave rise to the name 'Ribband Group'. The Cambrian and lower Ordovician strata were deformed in mid-Ordovician time by an orogenic event, the Monian, which was localised to the Leinster region and affected the southeast of the region more intensely than the northwest (Tietzsch-Tyler et al., 1994; Gallagher et al., 1994). In the upper Ordovician, further sediments and volcanic formations were deposited on the submerging Monian landmass, forming the Duncannon Group. Outcrops occur in Wicklow in the Avoca district, and in Wexford as a 6-8 km wide belt sandwiched to the north and south by Ribband Group metasediments (Figs. 1 and 2). In Wicklow the Duncannon Group incorporates the Avoca Volcanic Group (AVG, formerly the Avoca Formation) which comprises dominantly rhyolitic lavas, chloritic tuffs and slaty mudstones and hosts stratiform sulphide mineralization, described below. In earlier interpretations (e.g. Brück et al., 1979) the Duncannon Group was regarded as mainly volcanic, whereas Tietzsch-Tyler et al. (1994) include all post-Monian sedimentary rocks in this Group.

During the Late Silurian to Early Devonian Caledonian Orogeny, the previously deformed pre-Monian rocks were further folded together with the younger Ordovician rocks. A major period of shearing towards the end of the orogeny generated northeast-oriented deformation zones, one of which occurs in the Avoca – Goldmines River area (Williams et al., 1986). The Leinster Granite batholith and satellite granitic plutons (Fig. 1) were emplaced into these actively deforming shear zones in the Early Devonian around 405 Ma (O'Connor and Brück, 1978; Gallagher et al., 1994). Gold, tungsten, tin and lead-zinc mineralization is associated with thermal metamorphism and hydrothermal fluid circulation accompanying batholith emplacement (McArdle et al., 1989).

In the vicinity of the Goldmines River (Fig. 3), bedrock comprises low-grade metasedimentary rocks, mainly dark grey phyllites and quartzites of the Kilmacrea Formation, with intrusive sheets of granite, felsite and dolerite oriented parallel to the regional schistosity. Subordinate basic to intermediate lavas and tuffs, metamorphosed to chloritic and sericitic schists, occur within the Ribband Group succession which is stratigraphically overlain to the northwest by the AVG. The AVG outcrop width tapers southeastwards and the tapered end abuts the sigmoidal-shaped Croghan Kinshelagh Granite (Fig. 3) although some authors (e.g. Fritschle et al., 2018) consider the Duncannon Group to extend further southwest enveloping the granite outcrop.

The bedrock geology of North Wexford is similar to that of southern Wicklow, although the AVG is not represented in Wexford. Duncannon Group metasediments and volcanic rocks, comprising the Campile Formation, form a NE-SW belt which is demarcated on the south side by the Courtown-Tramore Fault (Tietzch-Tyler et al., 1994). This fault abuts the Campile Formation against Lower Ordovician slates and siltstones (the Ballyhoge Formation). To the north of the Campile Formation outcrop are stratigraphically older grey, green and purple slates of the Ribband Group (the Oaklands and Ballylane Formations). In the Duncannon Group outcrop, volcanic rocks comprise around one quarter of the rock volume, and are mainly felsic with lesser intermediate and mafic volcanic rocks and dolerite sills. The felsic rocks include rhyolitic lavas, tuffs and agglomerates within grey and brown slaty mudstones. Sheet-like intrusive masses of granite occur in this belt to the southwest of Enniscorthy, notably in the Adamstown area included in this study (Fig. 1). West of the study area, the Leinster Granite outcrop forms upland moors. This granite is dominantly a two-mica granodiorite-granite of S-type affinity which has higher concentrations of large-ion lithophile and light rare earth elements than typical granite (Brück and O'Connor, 1977). Chemical characteristics of the granites and volcanic rocks suggest that during their formation, the Leinster region was in a transitional position between a volcanic island arc that extended from County Waterford to the English Lake District and a back-arc basin in North Wexford – Wicklow.

Gallagher et al. (1994) demonstrated that the Croghan Kinshelagh Granite (Figs. 2 and 3; Croghan Complex of recent literature), cropping out west of the Goldmines River, is an older intrusion than the Leinster Granite. Instead, this granite intrusion is contemporaneous with Upper Ordovician (Llandeilo- Ashgill) volcanic rocks that outcrop around Avoca. Relatively high Th, Y, Nb and REE concentrations contrast the Croghan Kinshelagh Granite to other granite types in SE Ireland. However, recent geochronological and geochemical studies (Fritschle et al., 2016; Fritschle et al., 2018) have established that the Croghan Complex comprises discrete older and younger units. The older granite is correlative with AVG volcanism and has been deformed with a penetrative fracture cleavage similar to the AVG rocks, as described by Gallagher et al. (1994). The younger granite intrusion is undeformed and cuts across S1 deformation in the wallrock. Crystallization ages of 456.9 ±2.4 Ma and 455.4 ±2.8 Ma for the younger granite are c. 6 Ma younger than the AVG age of 462.6 ±3.5 Ma (Fritschle et al., 2016). These dates and structural features constrain the date of deformation representing a major arc accretion event at c. 460 Ma.

Bedrock mineralization

Table 1 and Fig. 2 summarise occurrences of bedrock mineralization in the area under consideration. Whilst the Avoca VMS deposit is clearly the most economically significant mineralization in the region, it is unlikely to have contributed placer gold to the Goldmines River area to the southwest. This is because of Avoca's peripheral geographical positon, the very fine particle size of gold reported from the VMS mineralization (Milner and McArdle, 1992), the size range of gold associated with similar deposits elsewhere (Huston, 2000), and the prevailing glacial transport regimes discussed below.

Banded iron formation that crops out on the Moneyteige–Ballycoog Ridge adjacent to the Ballinvally River (Figs. 2 and 3) hosts minor epigenetic Cu-Pb-Zn-Bi-Au mineralization described by McArdle and Warren (1987 a,b), Ixer et al. (1990) and Milner and McArdle (1992). McArdle and Warren (1987b) note that the major iron minerals are magnetite and siderite with sparsely disseminated pyrite and chalcopyrite, and that the mineralization is richest where it has been remobilised along faults. Chalcopyrite-rich samples assayed 0.2–0.5 ppm Au suggesting that gold is associated with chalcopyrite, which at outcrop weathers to hematite and limonite thereby liberating the gold.

Elsewhere in the Goldmines River area, stratabound Au-As-Fe-S mineralization has been identified by company exploration at the Mary Ellen and Maclaren zones (Figs. 2 and 3). These stratabound zones occur in the top-most interval of the Ribband Group marking the transition from sedimentary facies to volcano-sedimentary facies of the Duncannon Group (McKillen, Tyler and Associates, 2009). Similar associations have been reported from various localities throughout the study area in County Wexford. For example, exploration results reported by IMC (2013) in the Knockbrandon, Kilmichael-Ballyowen-Ballygarrett and Boley prospects in County Wexford (Fig. 2) indicate that, although broadly stratabound, the mineralization occupies ENE trending shear zones that are slightly oblique to lithological strike. Visible gold occurs in quartz veins within the shear zones. No detailed mineralogical information is available concerning this form of mineralization. However, it appears to be structurally controlled, often occurring at lithological contacts, and may be comparable in origin to the sulfide-hosted gold mineralization in the Kilmacoo deposit (Table 1).

Quaternary geology

Geochemical and mineralogical studies of sediments need to take into account the mobilization of material by various surface processes. Ireland was repeatedly glaciated during the Pleistocene, and at various times ice sheets covered most if not all of the area shown in Fig. 1, and certainly all of the area shown in Fig. 2 (Knight et al., 2004). In Ireland the most recent glacial epoch is referred to as the Midlandian. Consequently a wide variety of glacial and fluvioglacial erosional landforms and deposits occur in the study area. Located west of the area, the Wicklow Mountains supported an ice dome from which ice flowed radially (Warren, 1993). In the Avoca – Goldmines River area, SE- to ESE-oriented glacial striae mapped by McArdle and Warren (1987a,b) indicate that this radial ice flow would have dispersed detritus southeastwards across the study area (Fig. 2). Avoca and Goldmines River lie several kilometres beyond the western limit of shell-bearing glacial sediments deposited by southward- and south-westward-flowing ice streams in the Irish Sea basin (Fig. 2). Consequently, we assert that glacial processes could not have transported detritus from the Avoca VMS deposit or Kilmacoo Au deposit south-westwards to the Goldmines River area during the Midlandian glaciation.

In Wicklow, the effects of glacial processes are dependent upon valley orientation. East of Aughrim, the Aughrim River valley follows a ESE-trending course cutting through the prevalent structural grain (Figs. 2 and 3) and during glaciations is likely to have experienced a large ice flux (ice streaming) with associated transport of detritus. Perpendicular to this ice flow direction is the Goldmines River valley in which valley-side deposits are more prominent on east-facing slopes in the lee of the ice flow. McArdle and Warren (1987b) noted that sections through valley-side deposits show a stratigraphy of two distinct Quaternary deposits: a compact till unit up to 6 m thick overlies a clast-supported deposit of angular, locally-derived bedrock fragmented by gelifluxion. Underlying the till unit in the valley bottom, the geliflucted debris interdigitates with stream-washed debris. This suggests that the Ballinvally placer deposit was contained in sediments which pre-dated the Midlandian glaciation. McArdle and Warren (1987b) conclude that preservation of these pre-glacial sediments was facilitated by the transverse direction of the ice flow across the deeply incised valleys now occupied by the Ballinvally and Monaglogh Rivers (Fig. 3).

In Wexford south of the Croghan Kinshelagh upland area (Fig. 2), the outcrop extent of the Ribband Group is characterised by relatively low, subdued topography extensively covered by glacial deposits. Igneous rocks in the Duncannon Group form ENE-WSW oriented bedrock ridges. Gaps in these ridges, where the present day rivers flow across the structural grain, may have resulted from erosion along N-S oriented faults that segment the Duncannon Group outcrop (Fig. 2).

Methodology

Collection of placer gold and other heavy minerals

Gold grains were collected using the specialist field techniques described by Leake et al. (1997) which permits co-collection of heavy mineral concentrates (HMC). Material was collected from 30 sites in the study area selected for their potential to host elevated concentrations of gold particles, such as bedrock traps and point bars. All samples were collected from active, modern fluvial systems. Samples from 'first order' streams were favoured because these yield more valuable information on the provenance of placer gold than samples from trunk drainages which may contain gold grains from disparate sources (e.g. Chapman et al., 2010a).

Leake et al. (1997) suggested that a sample population of 30 particles would provide a satisfactory inclusion signature, based on their experience of observing inclusions in around 20% of the gold grains. This study has adopted a methodology in which far more gold grains have been collected, firstly, because the inclusion abundance in some samples was far lower, which necessitated resampling, and secondly because studies such as Moles and Chapman (2013) and Chapman et al. (2016) illustrate the benefit of larger data sets when characterizing populations of placer gold grains derived from multiple sources. Even so, in some cases only small numbers of inclusions were observed (e.g. Askamore: Table 2). Resampling over a period of several years also permitted evaluation of the reproducibility of alloy data for specific stream locations. Figure 4 A shows that very similar cumulative percentile Ag plots were obtained when resampling the same locality. This increases confidence that differences in the shape of the curves between sites are geologically significant and are not a consequence of sampling variations.

A total of 2160 detrital gold particles were used in this study, the data for 619 of which were previously reported by Chapman et al. (2006). Although detrital gold was recovered at every locality, the abundance varied enormously (Table 2). Collection of HMC samples was undertaken in order to provide semi-quantitative data on the abundance of heavy minerals other than gold, with a view to illuminating particle mobility in the surficial environment and potentially identifying mineral species genetically linked to gold mineralization (McClenaghan, 2011).

Analysis

Field-panned HMC were refined at the University of Brighton using heavy liquid separation (di-idiomethane) to remove mineral particles with a specific gravity of less than 3.3. Estimates of the modal mineralogy of HMC were obtained using X-ray diffraction (XRD) of powdered sub-samples, followed by mineral matching and semi-quantitative processing of the spectra. It is emphasized that the study aimed to compare the bulk mineralogy of the samples: the techniques employed do not reveal minerals in the HMC that are present in trace amounts (<1-2%). Portable XRF measurements of compressed powdered samples were used to qualitatively confirm the identity of minerals which have similar XRD spectra but contrasting geochemistry, such as cassiterite and magnetite. Due to spectral similarities, staurolite is difficult to distinguish from garnet in samples with large proportions of garnet and lesser staurolite.

The gold grains were mounted in resin blocks which were ground and polished to expose cross-sections through grain cores for microchemical analysis at the University of Leeds according to the methods of Chapman et al. (2000b). Quantitative analysis of gold and alloying elements was carried out using a Cameca SX50 automated electron microprobe (EMPA), fitted with three wavelength spectrometers and an Oxford Analytical 10/55s Energy Dispersive System (EDS). The EMPA was operated at 20kV and 50 nA, with a 30 second counting time for each element. Background counts were determined by a 30 s count off-peak. The standards employed were pure Au, Ag, Cu, and HgS. An internal standard of 81.5 % Au and 18.5 % Ag was employed in each batch of analyses. Detection limits were Ag: 350 ppm, Hg: 2,800 ppm, and Cu: 200 ppm. All analyses are reported in terms of mass % unless otherwise stated. Identification of specific mineral inclusion species was carried out using a Camscan Series 4 scanning electron microscope (SEM) operated at 25 kV fitted with an Oxford Analytical 10/25s EDS system, also at the University of Leeds.

Data presentation

Heavy mineral assemblages and Tellus geochemical data have been depicted as pie charts and proportional symbols respectively on maps of the study area (Figs. 5 and 11). It is emphasized that heavy minerals are expressed as proportions of the HMC sample which constitutes a variable fraction of the bulk sediment. Consequently no direct relationship is expected between these mineral proportions and the Tellus data for geochemical compositions of sieved stream sediment samples.

The abundance of detrital gold is typically highly variable in auriferous regions, but local high abundances may provide useful information on the distribution of bedrock source(s) particularly in first order drainage. Meaningful quantification of detrital gold grain abundance is challenging because of the extreme variation in concentrations at specific sampling sites due to hydrodynamic processes and operator skill, as discussed later. The locations of old placer workings provide a clear indication of local high concentrations, although abundances of detrital gold may now be low due to historical extraction. Elsewhere, detrital gold abundance at sample localities has been defined as very low, low, medium or high (Table 2, Fig. 6 A) where 'high' corresponds to recovery rates of dozens to hundreds of grains per hour of sluicing and panning activity, whereas 'very low' corresponds to a recovery rate of one or two grains per hour.

Representation of information generated by microchemical characterization is less straightforward to present spatially. Silver compositions of individual sample populations reflect either the compositional variation of a single source or the compositional ranges of multiple sources. In the second case, the presentation of a single statistical measure such as a median is usually inappropriate, and representation by use of cumulative percentile plots for each population is preferred (e.g. Fig. 4). Using this form of presentation, the Ag range and relative proportion of grains of similar Ag contents may be easily seen, and comparisons between samples quickly established. In Wexford, the majority of sample populations yielded sub-parallel shallow-gradient cumulative frequency trends with 5–20% of particles forming a steeper 'tail' of Ag-rich compositions (Fig. 4 B). In such cases the populations may be adequately represented by a median value (i.e. %Ag content at the 50% percentile), and this measure has been depicted on maps for comparison with other data sets. Class intervals have been defined on the basis of breaks in the slope of the cumulative Ag curve (Fig. 4 C) depicting the median values for all localities at which 4 or more gold grains were obtained (Table 2).

In contrast, sample populations from the environs of Croghan Kinshelagh in Wicklow generally exhibit a wide variation both in Ag content, and in profiles on a cumulative frequency plot (Fig. 4 D). Considerations of specific inclusion assemblages in conjunction with limited ranges of alloy composition have identified specific gold 'types' defined by their microchemical signatures. These types are present to different extents at each locality, explained below. In this particular area the distribution of these gold types is informative, whereas information is lost through the adoption of a single statistical measure such as the median %Ag value.

In this study, 20 opaque mineral species have been recorded as inclusions within gold grains (Table 2). Spider diagrams (Chapman et al., 2017b) permit quick comparison of the importance of major inclusion species whilst also recording the presence of small numbers of unusual minerals, such as native bismuth, whose presence may be informative.

While we focus on the microchemical signature of gold grains from sample localities, in some cases it has been helpful to consider the size and morphology of gold grains within a population to provide an additional context for the interpretation of compositional data.

Results

Mineralogy of heavy mineral concentrates

Proportions of heavy minerals in the concentrates are given in Table 3 and displayed as pie charts in Fig. 5. Garnet is ubiquitous throughout the region and staurolite is commonly associated with garnet in the north and south of the study area, consistent with previous HMC analyses by Malone (2007). These minerals are constituents of Ribband Group metasediments within the aureole of the Leinster granite and we ascribe their eastwardly dispersion to glacial transport during the Midlandian and perhaps also earlier glaciations. Locally, the dominance of garnet is reduced because of geographically focussed inputs of other heavy minerals derived from local lithologies. Ilmenite is an important component of the HMC at localities in the environs of mafic lithologies within the Duncannon Group in Wexford and the Ribband group in Wicklow (Fig. 2). Other minerals are recorded in elevated concentrations in spatially coherent clusters, for instance monazite in central Wexford, cassiterite at Askamore, Boley Lower and Milshoge in Wexford and some localities in Wicklow, ferberite at Askamore and Boley Lower, and chrome spinel at Ballygarrett and nearby sites. In the Goldmines River area, locally abundant hematite is most likely derived from the BIF outcrop on the Ballycoog-Moneyteige Ridge, as discussed later. Magnetite is abundant only in samples from Coolbawn River and from the Ballinvally River sampled at the main historical extraction site, the 'Red Hole'. The concentrates at these two sites have a striking similarity in heavy mineral proportions which contrast with surrounding sites (Fig. 5).

Detrital gold characteristics

As shown in Fig. 6 A, the abundance of detrital gold in stream sediment varies widely across the study area. The historical gold workings in Wicklow likely exploited concentrations of placer gold far in excess of those present at sample localities in Wexford where there is no history of artisanal mining. In north Wexford, scattered sites returned relatively high abundance against a background of average to low abundance. Relatively high abundances were recorded at four localities: Boley Lower, Milshoge, Ballykale and Ballygarrett (Fig. 6 A).

High abundance of detrital gold may be ascribed to either autochthonous or allochthonous processes and it is clearly advantageous to know which is prevalent in areas that are the focus of exploration campaigns. In this regard, information on gold particle size and morphology may be usefully applied. The coarse particle size of rough gold near the Red Hole in the Ballinvally River strongly suggests very local derivation (Maclaren, 1903), as does the apparent influx of gold particles to around 1g in the middle reaches of the Monaglogh River recorded during the present study (Fig. 7 A, B). Flaky gold from Milshoge (Fig. 7 C) is typical of gold particles recovered in Wexford, although rough gold characteristic of proximal derivation is dominant at Ballygarrett and Boley Lower.

Polished sections through gold grains embedded in resin exhibit various microtextural features when viewed with a scanning electron microscope in back-scattered electron mode. Small inclusions of sulfides and other metallic minerals represent the associated hypogene mineralogy (Fig. 8 A, B). Commonly observed gold-rich rims are attributed to silver depletion in the modern surficial environment (Groen et al., 1990), and are not considered further. Internally, gold grains from the Goldmines River area are mostly homogeneous in alloy composition (e.g. Fig. 8 C), but in contrast, many gold grains from the Wexford localities show internal heterogeneity (Figs. 8 D, E). These grains commonly have complex textures in which Ag-rich alloys appear to have overprinted a pre-existing alloy and a third phase of nearly pure gold forms rims and/or tracks. Processes that contributed to this heterogeneity, and the significance of the contrasting appearance of Wicklow and Wexford gold alloys, are discussed later.

Evaluations of the microchemical information exhibited by regional sample sets normally start with consideration of the alloy content of the various sample populations (e.g. Moles and Chapman, 2013; Chapman and Mortensen, 2016). While silver is ubiquitous as an alloy component, Cu and Hg were recorded only sporadically in grains from the region. The highest Cu values of 4.6% and 4.3%, recorded in gold grains from Ballyshannon and Ballykale respectively, are anomalous whereas the majority of grains have values close to or below the instrumental detection limit of 0.02% Cu. Therefore Cu values do not constitute a robust data set for quantitative treatment. Similarly, detectable Hg values were largely absent. Consequently neither Cu nor Hg are considered further as discriminants.

Sample suites from Wicklow and Wexford differ fundamentally in the nature of the ranges of silver present within individual sample populations. As discussed above, the generic form of the cumulative frequency curves of %Ag in all Wexford sites has allowed their characterization using a single median value, presented in Table 2, ranging from 3.2% Ag at Coolnacon Bridge to 8.3% Ag at Huntingtown. Three class intervals of median %Ag (low <5.5, medium 5.5-7.5, high >7.5) were chosen on the basis of the form of a cumulative percentile plot of median % Ag values (Fig. 4 C) and these categories have been indicated on Fig. 6 B. There appears to be little or systematic variation in Ag content of the Wexford sample suites with location, except that those around Adamstown in the south appear to contain slightly less Ag. Neither is there an overall correlation between Ag content and underlying lithology or heavy mineral association (Fig. 5), or spatial relationships correlating with ice flow direction (Fig. 2).

Contrasting characteristics are exhibited by detrital gold from each of the most important historical placer mining localities around Croghan Kinshelagh namely Ballinvally, Coolbawn and Monaglogh Rivers (Figs. 3 and 6 B). Gold from the Monaglogh River exhibits a high Ag sub-population that comprises around 40% of the grains (Fig. 9 A). This high-Ag alloy is largely absent at the other two localities. The relatively wide range of Ag contents observed within these populations, which invalidates the use of median %Ag values for classification, has directed our attention to the use of inclusion assemblages as the primary discriminants. At all three locations, the majority of arsenopyrite inclusions are hosted by gold grains with a narrow range of c. 9-14% Ag as shown in Fig. 9 A. Galena and native bismuth inclusions have been grouped because of their intimate association (e.g. Fig. 8 C) and these inclusions were observed within gold alloy of a lower Ag range (indicated by a horizontal line in Fig. 9 A). These tend to be mutually exclusive with the alloy range of gold grains that host arsenopyrite inclusions.

The Ag ranges of detrital gold samples collected to the north and northwest of Croghan Kinshelagh are depicted in Fig. 9 B. In these samples are dominated by low Ag gold alloys (type 1) that account for 50% to 90% of the total inventory (cumulative percentile), with very few grains containing ≥15% Ag. The plots for samples from the Clone and Ballintemple streams are strikingly similar. The low Ag, galena-bearing gold type identified in Fig. 9 A is also displayed in Fig. 9 B, where it corresponds to the low Ag portion of all other curves. Gold alloy in the range 9-14% Ag containing arsenopyrite inclusions is an important component of the overall population in the Goldmines River samples, but is absent in gold from the Ow and Clone localities.

Apart from galena and arsenopyrite, other mineral species occur in these samples, but their low overall abundance (Table 2) precludes a similar analytical approach. Gold 'types' identified by inclusion suites and range in Ag content of the host alloy have been defined broadly in Table 4. These types are interpreted to represent gold sourced from different mineralizing events, but there is no necessity for each type to exhibit mutually exclusive Ag contents, and no reason why a 'diagnostic' inclusion in one type should not be present, although rare, in another type.

The spatial variation in microchemical signature of detrital gold in the Ballinvally and Monaglogh River valleys was investigated by sampling upstream of the main placer areas and in tributary streams. Gold from upstream of the old workings yielded very similar Ag profiles to the richer areas downstream, whereas samples from tributaries showed a narrower compositional range (Fig. 9 C, D). Galena and arsenopyrite are the most common inclusion species although their proportions vary between gold types, as shown in Table 4. Type 1 gold exhibits the highest ratio of galena to arsenopyrite. Inclusions of native bismuth are extremely rare in general in gold grains, but the three observed here all conform to the type 1 alloy signature. In type 2 gold, the proportions of galena and arsenopyrite are approximately equal. In type 3 gold, arsenopyrite is far more common than galena and there is a higher abundance of pyrite with occasional pyrrhotite. Chalcopyrite is present in gold types 1 and 2 but is absent in type 3.

The above discussion has focussed on arsenopyrite and galena because these are the most abundant inclusion species. Using the full inclusion suite (Table 2), 'spider plots' have been generated (Fig. 10) by which the entire suite of inclusion minerals may be compared. Fig. 10 A shows the contrasting assemblages within the three gold types identified in the Croghan Kinshelagh area of County Wicklow as described above. For this geographically broader comparison, the plots incorporate inclusions recorded within all sample populations from each main valley, i.e. they also include inclusion data for gold obtained from tributaries and headwaters.

Presentation of the inclusion data for the Wexford sample suite is more challenging. The small number of inclusions recorded at each locality precludes meaningful comparison of individual assemblages such that some form of grouping into data sets is required, but this approach could mask locally dominant signatures. Two rationales for data grouping have been explored. Figure 10 B compares the inclusion signatures of gold from sample localities in the central Wexford area grouped according to bedrock stratigraphy at sample sites. In this approach each group shows broad mineralogical similarities, although Sb-bearing inclusions are present only at Boley Lower within the Ribband Group, and at Hyde Park near the Ribband/Duncannon Group contact.

A second approach is to use the heavy mineral concentrate data as a guide to forming the data sets. As noted earlier, heavy mineral assemblages at Boley and Askamore are atypical as they are dominated by cassiterite, ferberite and monazite. This suggests the presence of local felsic igneous bedrock, which in turn raises the possibility of different styles of local gold mineralization. Figure 10 C compares the inclusion signatures of gold from Askamore and Boley Lower with others from localities within the Ribband Group outcrop. The gold from Boley generally conforms to the regional signature, except the proportion of Sb-bearing inclusions is notably higher. In contrast, gold from Askamore differs from the regional norm through the absence of galena and the relatively strong Te and Se signature of the inclusion suite.

Results of the regional stream sediment geochemistry program

O’Connor and Reimann (1993) reported the first comprehensive regional geochemical study of SE Ireland. This was based on analyses of nearly 2000 sieved (fine fraction) stream sediment samples that were collected in the period 1986-1990 from 1st and 2nd order streams at an average spacing of 1 per 4 km^2. In this dataset, they identified three significant geochemical associations: (i) a close spatial correlation of Li, Ta, U and W with granitic lithologies, (ii) a Cu, Sb and Au signature interpreted as indicative of a volcanic association, and (iii) a Cr-Ni association which they ascribed to small local occurrences of ultramafic lithologies. Relative to regional values, elevated Au concentrations were found throughout the Ribband and Duncannon Group outcrop on the SE side of the Leinster Granite, with anomalous Au values in samples in the Tinahely-Shillelagh zone of tourmaline-bearing Ribband Group metasediments (Fig. 2). Samples from the Avoca – Goldmines River area did not show Au enrichment relative to the regional levels although a single high value (discussed later) was found in the Coolbawn River.

The current, Ireland-wide, Tellus regional geological surveying program included re-analysis by XRF of the original sieved sediment samples obtained for the study reported by O’Connor and Reimann (1993). The re-analyses, using methods reported by Smyth (2007), were undertaken by the Geological Survey of Ireland and funded by the Department of Communications, Energy and Natural Resources. The new data set was made publically available in 2016 (Knights and Heath, 2016). Several examples of the data sets are presented in Figure 11. The concentrations and distribution of various elements reported in the Tellus database can be interpreted in the light of their probable significance for gold mineralization. Elements such as Cu, Sb, As, Pb and Bi could be associated with specific gold sources, whereas Sn, W, Cr and Ni are more likely to be derived from other styles of mineralization but their distribution may provide evidence for glacial dispersion (McClenaghan and Paulen, 2018) which may have also influenced detrital gold distribution (discussed later).

Less than 5% of the stream sediment samples collected within the study area returned elevated concentrations of gold in the range 0.1 to 1.5 ppm (Fig. 11 A). Fine fraction sediment samples with >0.5 ppm Au are mostly located in a southeast-northwest trending belt between Camolin and Carnew. There appears to be no spatial association between bedrock geology and Au enrichment in sediments, indeed the SE-NW trending belt is perpendicular to the ‘Caledonian’ trend of the bedrock and crosses outcrops of both Ribband and Duncannon Group rocks. This belt encompasses the Tombreen, Askamore, Boley, Kilcloran, Milshoge and Ballyeden detrital gold sites of the present study (Fig. 2). In addition, to the east of this belt, an isolated auriferous stream sediment sample is located close to the Ballygarrett auriferous float occurrence documented by Chapman et al. (2006). Further stream sediment Au anomalies occur west and southwest of Arklow and southwest of Camolin although these areas were not sampled during the gold grain study reported here.

Detrital gold was recovered during the current study from several areas where the Tellus data indicates that fine-fraction sediment is not auriferous. Examples are south of Camolin (South Corbetstown), south of Gorey (Coolnaveagh and Ballykale), west of Ballycanew (Ballyduff) and east of Inch (Hyde Park and Cullenoge) (Table 2, Figs. 2 and 11 A). In the Avoca – Goldmines River area, concentrations of Au >0.1 ppm occur in only one Tellus sample (Fig. 11 A) which is located downstream of the Coolbawn River detrital gold sample site of the present study. Interestingly, sediment samples from the Monaglogh and Ballinvally River catchments, re-analysed in the Tellus programme, do not contain detectable levels of Au. Possible explanations for this are discussed later but it is noteworthy that studies of other glaciated terranes show little correlation between gold in sieved sediment and in heavy mineral fractions (McClenaghan and Paulen, 2018).

Neither Cu or As show close associations with Au values in the Tellus dataset (Fig. 11 D, E) which is perhaps surprising given the regional descriptions of Au-As-Fe-S bedrock mineralization. Higher Cu and As values were recorded around Avoca and there are clusters of As values in known auriferous areas such as the Goldmines River and in the west of the study area (4 km north and 5 km east of Carnew). Antimony concentrations in fine fraction sediments range up to 12 ppm and display a strong spatial trend (Fig. 11 F) with values >3 ppm Sb largely confined to Kilmacrea Formation (Duncannon Group) metasediments on the southeast side of the Avoca – Ballycoog-Moneyteige zone, i.e. in the stratigraphic footwall to the stratabound Cu-Fe mineralization. Additionally, high Sb values are recorded in the central sections of the Ballinvally and Monaglogh Rivers. Moderate Sb concentrations occur east of this and in the southern part of the study area in Wexford. Lead (Fig. 11 C) shows anomalous concentrations at Avoca in the same sediments that are enriched in Sb, and in one sample from the west of Croghan Kinshelagh. Similarly, Bi is enriched in the fine fraction stream sediment in the environs of the Croghan Kinshelagh granite, the BIF on the Moneyteige ridge, and the AVG outcrop (Fig. 11 B). There is also an isolated high Bi anomaly 2-3 km ESE of Camolin.

The distribution of Cr, Ni, W and Sn correlates to specific lithogies and in some cases provides an indication of general glacial dispersion. Chromium concentrations are generally <200 ppm except for a prominent linear belt extending 6-8 km NNW from Ballygarrett to Cummer (Fig. 11 G) where values up to 1000 ppm are recorded. The linear anomaly lies within Ribband Group metasediments but is discordant to the country rock strike, and can be ascribed to glacial and fluvial dispersion southeastwards from the chromite-bearing serpentinite outcrop near Cummer in north Wexford (Gallagher, 1989). Moderate Ni enrichment (Fig. 11 H) is associated with the Cummer serpentinite and with Duncannon Group outcrop between Avoca and Arklow. Tin concentrations are highest at the margins of the Leinster and Croghan Kinshelagh granites (Fig. 11 I). The distribution of Sn and of W (Fig. 11 J) indicates mineralization at these granite margins, notably the Ballinglen-Tinahely zone of W-Sn-Au mineralization described by Steiger and Bowden (1982) and Kennan et al. (1986) (Table 1), showing a broad dispersion consistent with the prevailing ice flow direction towards the southeast, as described above.

Discussion

Implications of the stream sediment geochemistry dataset for regional gold mineralization

There are two ways in which the stream sediment geochemistry data set can inform exploration for gold mineralization within the study area.

Firstly, the data set permits evaluation of the dispersion of chemically distinctive mineral particles within a surficial environment which has been subject to multiple episodes of glaciation. Tungsten, tin and chromium exhibit well defined dispersion trains form source lithologies as described above. As discussed in a later section, these elements are likely contained within the resistate oxide minerals ferberite, cassiterite and chrome spinel. The linear pattern of down-ice dispersion of chromium from a point source serpentine outcrop (Fig. 11 G) indicates the potential distance and direction of dispersion of other resistate minerals such as gold.

Secondly, the abundance of gold and its correlation with other elements commonly regarded as 'pathfinders' may generate a multi element anomaly suggestive of a particular style of mineralization, which may then be correlated with our understanding of bedrock geology. Elevated gold concentrations in stream sediment, indicated by the Tellus analyses, are widespread in the study area but there is little correlation between Au values and other potential gold indicators such as As and Sb which occur sporadically (Fig. 11 E and F). Bismuth enrichment in fine fraction stream sediments (Fig. 10 B) appears to be a generic marker for mineralization associated with the Croghan Kinshelagh granite and with the contemporaneous volcanic-hydrothermal expressions at Moneyteige Ridge and Avoca. The Tellus results for the Avoca area broadly correspond with till geochemistry reported by Moon and Hale (1983) who found that As, Sb and Bi enrichment in near-surface glacial sediments reveal the concealed Avoca mineralization which otherwise has a weak geochemical expression at surface.

Other element signatures may be related to known mineral occurrences, or specific lithologies. Anomalously high Pb and Cu occur in stream sediments in the vicinity of the disused mines at Avoca and at one site southwest of Croghan Kinshelagh (Fig. 11 C, D). Clusters of sites with relatively high Pb values occur southwest of Tinahely and of Camolin (Fig. 11 C) suggesting that Pb-bearing mineralization is also present in these areas. Moderately elevated Pb is spatially associated with the Duncannon Group outcrop in southern Wicklow, but not in Wexford where there is no difference between the Duncannon and Ribband Groups in terms of Pb concentrations in fine fraction sediments. Nickel is relatively enriched in sediments in the Duncannon Group outcrop in County Wicklow with anomalous levels south of Avoca (Fig. 11 H). Although a cluster of Ni enrichment is evident associated with the Cummer serpentinite outcrop east of Carnew, Ni does not show the extensive eastwards dispersion shown by Cr (Fig. 11 G), probably as a consequence of the relative instability of Ni-bearing minerals such as pentlandite in the weathering environment.

Interpretation of the HMC data set

Garnet and staurolite are volumetrically abundant constituents of Ribband Group metasediments within the aureole of the Leinster granite and we ascribe their eastwardly dispersion to glacial transport and post-glacial fluvial reworking into modern stream sediments.

The major gold-bearing catchments of Coolbawn, Ballinvally and Monaglogh all exhibit a strong magnetite signature, usually with haematite, although hematite has a low abundance in the Monaglogh River (Table 3, Fig. 5). Magnetite could be derived either form the oxidised granites of the Croghan Complex which outcrops at the Coolbawn site and in the headwater of the Ballinvally River, or from BIF formations (McArdle and Warren, 1987b; Ixer et al., 1990; Wheatley, 1971). Wheatley (1971) records the supergene alteration of magnetite to hematite (martitization) which would account for the spatial overlap of these iron oxides and variations in their relative proportions between sample sites. This precludes using magnetite as a diagnostic marker for erosional products of the BIF. Gallagher et al. (1994) mentions ‘accessory Fe ore’ in the Croghan Kinshelagh granite and mapped ‘magnetite-rich tuffs’ in that area. Localities of high ilmentite concentrations are focussed around the Croghan Kinshelagh granite and associated dolerite intrusions in Wicklow, but are more consistent throughout Wexford suggesting that minor intrusions of dolerite are widespread in the Ribband Group.

Barite was recorded in the HMC from Ballygarrett (Table 3, Fig. 5) which is suggestive of local mineralization since barite is mechanically unstable during transport in the surficial environment.

The local concentrations of cassiterite, ferberite and tantalite at Askamore (Fig. 5) and to a lesser extent at localities eastwards along the general glacial dispersion direction, suggest derivation from a currently unrecorded granitic intrusion.

Overall the HMC samples owe their diversity to a variety of local overprints of the ubiquitous garnet + staurolite signature. Minerals associated with ‘point sources’, notably monazite, cassiterite, ferberite, magnetite and chrome spinel, appear to have been dispersed in the region of a few kilometres eastwards of bedrock sources. This transport distance and direction accords with the dispersion of W and Cr from parent lithologies, as shown by the Tellus sediment geochemistry data set.

Interpretation of detrital gold characteristics in southeast Ireland

Internal alloy heterogeneity, ranges of alloy compositions, and mineral inclusion suites may all be used to compare gold from different sampling localities and in some cases to infer the nature of the source mineralization.

The contrasting internal textures of gold grains from Wicklow and Wexford (Fig. 8 D-F) indicate different conditions of mineralization. In Wicklow, alloy homogeneity suggests a stable precipitation environment and a single episode of deposition, although the exact conditions may vary spatially or temporarily, yielding gold grains of different compositions. In contrast, the texturally complex gold particles from Wexford may indicate episodic fluid influx and spatial dispersion of the mineralizing fluids, as discussed by Chapman et al. (2010a). Within the cores of heterogeneous grains, Ag-rich gold always postdates Au-rich alloy (e.g. (Fig. 8 E, F). Veinlets of nearly pure gold may cross cut these features but these have been ascribed to surficial alteration penetrating along crystal boundaries (Hough et al., 2009). Thus only the progression to Ag-rich alloy reflects evolution within the hypogene environment, a trend that is consistent with both falling temperature and decreasing availability of gold in the later stages of the hydrothermal regime (Gammons and Williams-Jones, 1995).

Our relatively high sampling density in the Goldmines River area, together with specific gold alloy inclusion associations replicated at different localities in this area, has enabled the definition of three gold types as summarised in Table 4, and illustrated spatially in Fig. 12 using pie charts. In the historic placer mining area, type 1 gold was identified in the Monaglogh and Ballinvally Rivers, but only as a minor component in the Coolbawn River (as evident in Fig. 9 A). The abundance of type 2 gold varies between the three main auriferous drainages but forms the majority of the population in the Coolbawn site. Type 3 gold is abundant only in the Monaglogh River.

Linking placer gold analyses to statistics describing production data to establish the signature of the most promising exploration target was advocated by Chapman and Mortensen (2016) and has proved useful again here. We can compare our results for the median Ag values of gold from the Goldmines River (Ballinvally and Monaglogh Rivers samples combined: 8.5%) and from the Coolbawn River (11.2%) against the bulk assay of historically recovered gold (7.82% Ag) recorded in returns to the Irish Mint (Kinahan, 1882). Given that type 1 gold has the least Ag, this suggests that type 1 gold contributed a disproportionately large mass with respect to the overall inventory of recovered placer gold, and hence probably represents the most attractive target for future exploration projects.

Figure 12 shows that the Ballinvally and Monaglogh River placer occurrences are adjacent to zones of Au-As-Fe-S mineralization. However, Fig. 9 B shows that arsenopyrite-bearing gold is typically associated with an Ag range of 9-14%. Thus in these catchments the known in situ localities appear not to match the most important placer signature, either in terms of alloy composition or mineralogy. The inclusion mineralogy of type 1 gold appears similar to the mineralogy of sulfide-sulfosalt mineralization (chalcopyrite, galena, sphalerite Cu-Pb-Bi sulfosalts) hosted by the BIF on Moneyteige Ridge (Fig. 12) reported by Ixer et al. (1990). These authors suggested that hydrothermal systems associated with local basic intrusions introduced the metals into the vein systems. McArdle and Warren (1987a,b) suggested that regional structural development may have formed conduits for fluids associated with the cooling of the Leinster Granite. Such a wider scale event better explains the distribution of type 1 gold (Fig. 12).

Ixer et al. (1990) comment on the close association of galena and native bismuth within samples of mineralized BIF. They ascribe this association to exsolution of previously existing more complex minerals. Figure 8 C shows a galena–native Bi inclusion in a gold grain from the Monaglogh River. Native Bi is the dominant mineral and it may be that the other native Bi inclusions observed in this study are also associated with minor amounts of other minerals which have not been revealed in section. The similarity between inclusion suites in type 1 gold and the mineralization at Moneyteige Ridge is consistent with the scenario of multiple occurrences of this gold type within the Wicklow study area. The Ag plots presented in Figures 9 C and D show variation between samples from within the catchments of the Ballinvally and Monaglogh rivers respectively. The most plausible explanation for the variation in signatures of sample populations from trunk drainage and tributaries is that different sources account for each.

Arsenopyrite was not recorded in either type 1 gold or in the hypogene mineralogy at Moneyteige Ridge reported by Ixer et al. (1990). Therefore type 2 gold may correspond to the Au-As-Fe-S type mineralization reported at such localities as the Mary Ellen Zone and the Maclaren zone (Table 1, Fig. 12). However arsenopyrite inclusions were not observed in gold from the Coolbawn River and the source association for this placer gold remains unclear. Type 3 gold may represent a compositional end member of type 2 gold.

The mineral inclusion assemblage of Wexford gold also shows a galena-arsenopyrite signature (Fig. 10 B). Bismuth minerals are absent whereas chalcopyrite, sphalerite and pyrite are more common than in the Wicklow samples. This inclusion mineralogy is compatible with the compositional range of Phanerozoic orogenic gold recorded throughout the British and Irish Caledonides as summarized by Chapman et al. (2000b).

The inclusion signature of the gold from Askamore appears different from the regional signature (Fig. 10 C), although the alloy composition is otherwise typical of gold in the region. The inclusion signature is based on a small sample set, but appears to indicate very low fS_2, owing to the presence of altaite (PbTe) and clausthalite (PbSe) but not galena. A distinctive heavy mineral suite dominated by cassiterite and ferberite with minor tantalite strongly suggests a previously unrecognised concealed granitic body, and this atypical local lithology may provide an underlying reason for the unusual inclusion mineralogy.

The diverse mineral inclusion assemblage in gold from Boley Lower contains a distinct antimony signature which distinguishes it from other samples in the region (Table 2, Fig. 10 C). The discovery of nearby in situ mineralization provides a plausible local source, but neither descriptions of the borehole lithologies nor the inclusion suite suggest a magmatic influence on the gold mineralization. In this case, the origin and significance of the ferberite and cassiterite components of the heavy mineral concentrate are uncertain but they likely represent glacial dispersion from the postulated granitic outcrop at Askamore and are probably unrelated to the gold mineralization. It seems more likely that the gold at Boley Lower is derived from a proximal source as suggested by the local abundance, gold morphology and distinctive microchemical signature.

Re-evaluation of previous models accounting for the Wicklow placer resource

Correlation of gold microchemical signature with the current limited understanding of in situ mineralization allows a re-evaluation of previous hypotheses which proposed various models for the source of gold in the Wicklow placers. These have ranged from local intra-valley sources (Weaver, 1835; Maclaren, 1903), sulfide mineralization at Moneyteige Ridge (Smyth, 1853; Kinahan, 1883; McArdle and Warren, 1987a and 1987b; Ixer et al., 1990), and auriferous gossans at Avoca (O'Brien, 1959). The potential of Avoca as a source may be discounted on the basis of ice flow directions (McArdle and Warren, 1987b), patterns of heavy mineral distribution (Fig. 5) and gold signature (Fig. 9 D). The potential for the BIF-hosted mineralization on the Moneyteige Ridge to represent an example of type 1 gold has been discussed above, as is the likelihood that such mineralization is more widespread in the region and not confined just to BIF host rocks.

The differences in signatures of sample populations of detrital gold from within individual drainages (Figs. 9 C, D and 12) leads us to favour a model in which intra-valley type 1 mineralization supplemented gold from the local Au-As-Fe-S style (gold types 2 and 3) to form rich gutter placers in a ravine-like setting at the Red Hole. In Fig. 12, pie charts representing the proportions of gold types are superimposed colour-coded catchment areas representing heavy mineral proportions, from which it is apparent that these show no consistent relationship. The decoupling of gold types from HMC mineralogy suggests that in the Goldmines River area, bedrock gold mineralization is not lithologically controlled, and is instead probably structurally controlled. This concurs with Standish et al. (2014) who, in interpreting lead isotope ratios in placer gold from southeast Ireland, favour two mineralization events that peaked at c.460 Ma contemporary with the Early Caledonian orogenesis and at c.400 Ma coincident with Late Caledonian granite emplacement.

Evaluation of glacial impact

The general lack of information describing in situ mineralization throughout the study area clearly inhibits proposing specific placer-lode relationships. In addition, speculation of these relationships based on microchemical characterization of detrital gold grains must take into account potential transport by glacial processes. In Wicklow, it is possible to infer limited transport of gold in the areas of historical gold working on the basis of the local large particle size of gold, detrital gold abundance and the distinctive and geographically constrained associated HMC signatures (Fig. 12). Elsewhere in Wicklow the overall similarity between HMC signatures irrespective of bedrock lithology (Fig. 5) is suggestive of a strong glacial influence. At many localities the low abundance of detrital gold is compatible with reworking from regionally-derived till. There are notable exceptions: both the Ballintemple and the Clone streams were minor targets during the gold rush, and gold from these localities produces a very similar Au alloy signature (Figs. 9 B and 12). Lyburn (1901) reported placer gold workings in the upper reaches of the Ow River, in the aureole of the Leinster Granite. It seems most likely that local occurrences of bedrock mineralization have generated these modest placers, but that some gold has been glacially transported and ultimately manifests as low concentrations in drainages elsewhere (e.g. Knockanode and Castlemacadam: Table 2, Figs. 3 and 12).

The degree to which glaciation has influenced the distribution of gold in the Wexford localities is less clear. Evidence from the dispersion of heavy mineral indicators has provided a guide to the direction and extent of glacial transport which, coupled with multiple occurrences of auriferous bedrock, would generate the Au distribution observed in both the Tellus dataset and the gold-grain study. At Ballygarrett, derivation of the placer gold from proximal bedrock is considered as likely based on (i) the discovery of nearby in situ mineralization (Table 1), (ii) relatively high abundance of detrital gold, and (iii) the abundant barite which is not observed in HMCs elsewhere (Fig. 5). Further evidence for specific local sources is provided by the abundance and pristine nature of gold grains at Boley Lower. At other localities, low abundances of gold are compatible with glacial-fluvial transport away from localised Fe-As-S mineralization, most of which probably remains undiscovered. We propose that multiple occurrences of a broadly similar of style of mineralization, coupled with small scale dispersion, account for the general similarity in compositional signatures of gold in the Wexford study area.

Evaluation of the strengths and weaknesses of each method and the advantages of a combined approach

The widespread Au enrichment in fine fraction sediment revealed in the Tellus dataset highlights southeast Ireland as a prospective region for gold mineralization. The sampling and analytical protocols ensure comparability across the region, and the geochemical data provide an efficient means of identifying broad areas of interest for multiple elements simultaneously. Conversely the methodology may be hampered by the ephemeral nature of non-resistate mineral species in the surficial environment, such as sulfides and sulfarsenides. This might explain why sediment geochemistry data for Au and As in Wexford does not show a spatial correlation.

The presence of Au within fine fraction sediments may be a consequence of ‘invisible’ gold within sulfides or attributable to small particles of native gold. In Wexford, where derivation from Au-As-Fe-S mineralization is proposed, the lack of correlation between Au and As suggests that any original mineralogical association between arsenopyrite and gold has been eradicated by chemical degradation. The same reasoning may be applied to any invisible gold once hosted by pyrite. Therefore, the gold values recorded in the Tellus data set almost certainly indicate small particles of free gold. The recovery of gold grains less than 150 µm in diameter ensures comparability between samples and is independent of the skill of field operatives. In some areas, detrital gold is almost all below this size threshold, for example in the present study, the Tellus data reports anomalous Au in tributaries of the Avoca River where coarser gold is extremely scarce (Table 2). This disparity may be a consequence of the predominantly fine size of gold grains present in the nearby Avoca VMS and Kilmacoo Au deposits.

The very high density of native gold enhances local segregation in a fluvial environment. The sample collection methodology used in O’Connor and Reimann’s (1993) survey and in the more recent Tellus programmes involve sampling the centre of the active channel, as this sedimentary environment is reproducible between sites. However, such high energy zones are unfavourable environments for the accumulation of particles of very high density. Additionally, gold grains are normally relatively scarce in sediment, and so a sampling protocol which involves collection of a fixed volume of sieved sediment does not offer the best methodology to establish the presence of detrital gold. In the present study, gold grains were recorded in moderate abundance at some Wexford localities (e.g. Camolin, Hyde Park and Ballykale) but this result is not reflected in the Tellus geochemical data set. In the Goldmines River area of Wicklow, the relatively coarse particle size range of gold may have influenced the collection of gold grains during O’Connor and Reimann’s (1993) survey, although other factors most likely influenced the generally low regional values. These factors include QA/QC issues in sample collection of the stream sediments in this area (K. Knights, pers. commun., 2018), and gold depletion owing to historical mining which frequently involved re-routing of the watercourse to yield a relatively impoverished channel.

Exploration programmes which involve the collection specifically of detrital gold grains adopt a completely different approach in which atypical sedimentary environments that preferentially concentrate gold are targeted (e.g. Leake et al., 1997). The success of sampling may be contingent upon the ability of the field operative to identify such areas, particularly if gold particles are scarce. This methodology involves spending sufficient time at one location to collect a sample, and consequently the period required to complete a survey may be difficult to predict. Sample collection by panning does not necessitate a pre-screening other than to remove >1 cm clasts. While offering the advantage of collection of gold particles with diameters >150 µm, retention of smaller gold grains during sluicing and panning is most certainly a function of the skill of the field operative.

In the present study, consideration of HMC mineralogy has helped to constrain the degree of glacial dispersion of minerals released from a point source, and this appears to broadly accord with similar conclusions drawn from the fine fraction sediment geochemistry. This information has been used to explore possible relationships between the microchemical signatures of gold from localities that could feasibly be within a dispersion train. For example, Avoca is an inadmissible source for gold in the Goldmines River area when HMC signatures are inspected (Fig. 5). Analysis of HMC samples provides an additional advantage in that this may reveal minerals which can only be ascribed to specific lithologies, which may not appear on existing geological maps due to poor exposure. At Askamore, this approach has permitted a robust interpretation of the mineralization which would not otherwise have been possible. In some cases, the same mineral may be derived from two or more local lithologies which can complicate interpretation of the mobility of the mineral in the surficial environment. For example, magnetite may be derived from granite and from BIF, as discussed above. In these cases it may be possible to establish the host lithology source of mineral grains through trace element analysis (e.g. Canil et al., 2016; Nakashole et al., 2018). HMC data sets rarely provide direct information on the nature of source Au mineralization because sulfides and other ore minerals do not survive in oxidising surficial environments. This observation is consistent with the decoupling of As and Au recorded in the Tellus stream sediment geochemistry dataset.

Distinctive gold particle size and/or morphology may help to infer the presence of local bedrock sources, particularly when used in tandem with compositional studies of the same sample population. Alloy heterogeneity may indicate whether the parameters controlling alloy composition were stable, suggestive of a regime which is sufficiently robust to buffer against chemical or physical change, or whether gold mineralization is a consequence of episodic, smaller volume fluid influx. Inclusions preserve the mineralogy of the hypogene source even when other components (sulfides etc.) are no longer represented in surface sediments, or potentially where the original Au-metal relationships have been obscured by anthropogenic contamination. Establishing the inclusion assemblage may also confirm the validity of a potential local hypogene source, or indeed categorically exclude it. Clear indications of specific possibilities of sources in areas of complex geology and geomorphology can indicate whether gold is likely derived from a single point source or multiple bedrock occurrences, and whether all in situ mineralization is genetically related. Such insights can greatly inform deposit models with the associated benefits for exploration targeting. In academic studies of gold metallogenesis, a further refinement is the use of lead isotope analysis of gold grains (Standish et al., 2014).

However, there are limitations to the adoption of gold grain studies. Firstly the technique is specific to gold, although Chapman et al. (2017, 2018) have advocated the use of detrital gold as a pathfinder for copper porphyry mineralization. Secondly, substantial field time may be required to collect sufficient detrital particles for study, particularly in areas where overall abundance is low. Selection of sample sites is of paramount importance, and the use of experienced field personnel is particularly advantageous in this regard, whereas the field skills required for collection of fines and HMC are relatively easily learned. Time spent searching for gold grains when they are in fact absent, is clearly inefficient and consequently gold grain studies may benefit from the results of previous standard stream sediment geochemistry to delineate areas for focussed study – although this was not the case in Wicklow. Thirdly, preparation and analysis, whilst not particularly difficult, are currently the preserve of a small number of facilities, and are time consuming and expensive in comparison to the established automated analytical procedures applied to sediment samples.

Whilst reconnaissance geochemical studies can provide a geographical focus for gold grain studies, the specific gold–element association revealed by analysis of inclusion suites may also inform interpretation of geochemical data bases. For example, the presence of arsenopyrite inclusions may underline the importance of As values in stream sediments. A spatial coincidence of Au and Pb sediment anomalies in urban areas could be ascribed to anthropogenic contamination, but knowledge of the gold grain inclusion suite may confirm whether such associations are genetic.

Conclusions

Each of the techniques employed here has contributed to an improved understanding of the gold metallogeny of SE Ireland and we propose that such an approach could be used to advantage in other regions of complex geology and poor exposure. The information provided by regional programs of fine sediment analysis is widely appreciated, and this study underlined the value of this standard approach, in that the geochemical dataset confirmed the widespread distribution of detrital gold in the study area. Nevertheless, on the basis of stream sediment geochemistry alone it would be reasonable to conclude that gold mineralization in Wexford represents the most attractive target, whereas interpretation of gold grain studies, together with consideration of historical accounts of mining, would strongly favour a larger gold endowment in Wicklow.

Co-collection of gold and heavy mineral suites provides two independent measures of heavy mineral dispersion, i.e. through mineralogical studies and consideration of gold particle size, morphology and composition. Studies of heavy mineral concentrates provide a context to interpret results of gold grain studies through evaluation of the mobility of resistate minerals in the surficial environment. However, unless source-specific indicator minerals are recovered in the HMC samples, they provide only indirect evidence for the nature and location of gold sources.

Gold grain collection programs are comparatively time-consuming and their success may be dependent on the skill of field operatives. However, compositional characterization of gold provides an effective way to establish whether sets of detrital grains from different localities share a common origin. This information may be applied in specific areas to prove or disprove genetic links between target in situ mineralization and local accumulations of placer gold. Assumptions of a genetic link between placer and lode gold may provide rationales for exploration projects but the hypotheses are rarely tested. In addition, the mineral inclusion suites permit direct correlation with global templates that link inclusion mineral species or assemblages to specific styles of hypogene mineralization. In this way, gold characterization studies provide more compelling evidence to interpret regional metallogeny than may be inferred by considering only the co-variance of elements in stream sediment geochemical datasets.

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REFERENCES

Brück, P.M., Colthurst, J.R.J., Feely, M., Gardiner, P.R.R., Penney, S.R., Reeves, T.J., Shannon, P.M., Smith, D.G. and Vanguestaine, M., 1979, Southeast Ireland: Lower Palaeozoic stratigraphy and depositional history, in Harris, A.L., Holland, C.H. and Leake, B.E., eds., The Caledonides of the British Isles – Reviewed, Geological Society of London Special Publication No. 8, p. 533-544.

Brück, P.M. and O'Connor, P.J., 1977, The Leinster batholith: geology and geochemistry of the northern units: Bulletin of the Geological Survey of Ireland, v. 2, p. 107-141.

Canil, D., Grondahl, C., Lacourse, T. and Pisiak, L.K., 2016, Trace elements in magnetite from porphyry Cu–Mo–Au deposits in British Columbia, Canada: Ore Geology Reviews, v. 72, p. 1116-1128.

Chapman, R.J. and Mortensen, J.K., 2016, Characterization of gold mineralization in the Northern Cariboo Gold District, British Columbia, Canada, through integration of compositional studies of lode and detrital Gold with historical placer production: a template for evaluation of orogenic gold districts: ECONOMIC GEOLOGY, v. 111, p.1321-1345.

Chapman, R.J., Allen, M.M., Mortensen, J.K., Wrighton, T.M. and Grimshaw, M.R., 2018. A new indicator mineral methodology based on a generic Bi-Pb-Te-S mineral inclusion signature in detrital gold from porphyry and epithermal environments in Yukon Territory, Canada: Mineralium Deposita, **53**, pp.815-834.

Chapman, R.J., Leake, R.C and Moles, N.R., 2000a. The use of microchemical analysis of alluvial gold grains in mineral exploration: experiences in Britain and Ireland: Journal of Geochemical Exploration, v. 71, p. 241-268.

Chapman, R.J., Leake, R.C., Moles, N.R., Earls, G., Cooper, C., Harrington, K., and Berzins, R., 2000b, The application of microchemical analysis of gold grains to the understanding of complex local and regional gold mineralization: a case study in Ireland and Scotland: ECONOMIC GEOLOGY, v. 95, p. 1753-1773.

Chapman R.J., Leake, R.C., Warner, R.A., Moles, N.R., Cahill, M.C., Shell, C.A., and Taylor, J.J., 2006, Microchemical characterization of natural gold and artefact gold as a tool for provenancing prehistoric gold artefacts: A case study in Ireland: Journal of Applied Geochemistry, v. 21, p. 904-918.

Chapman, R.J., Mileham, T., Allan, M.M. and Mortensen, J.K., 2017, A distinctive Pd-Hg signature in detrital gold derived from alkalic Cu-Au porphyry systems: Ore Geology Reviews, v.83, p.84-102.

Chapman, R.J., Mortensen, J.K., Crawford, E. and LeBarge, W., 2010a, Microchemical studies of placer and lode gold in the Klondike District, Yukon, Canada: 1. Evidence for a small, gold-rich, orogenic hydrothermal system in the Bonanza and Eldorado Creek area: ECONOMIC GEOLOGY, v. 105, p. 1369-1392.

Chapman, R.J., Mortensen, J.K., Crawford, E.C., and LeBarge, W.P., 2010b, Microchemical studies of placer and lode gold in the Klondike District, Yukon, Canada: 2. Constraints on the nature and location of regional lode sources: ECONOMIC GEOLOGY, v. 105, p. 1393-1410.

Dana Exploration PLC, 1992, Renewal report for RioFinEx Prospecting Licence 2053, Counties Wicklow and Wexford: Geological Survey of Ireland (GSI) open file report, 5 p.

Downes, K.M.J. and Platt, J.W., 1978, The Avoca-Ballard mineralized belt, Co. Wicklow: Journal of Earth Sciences, Royal Dublin Society, v.1, p. 121-133.

Fritschle, T., Daly, J.S., Whitehouse, M.J., McConnell, B. and Buhre, S., 2016, Arc petrogenesis in southern Ireland and the Isle of Man: Implications for Ordovician accretionary history and constraints from Late Caledonian plutonism: abstract of presentation at EGU General Assembly 17-22 April 2016 in Vienna, Austria.

Fritschle, T., Daly, J.S., McConnell, B., Whitehouse, M.J., Menuge, J.F., Buhre, S., Mertz-Kraus, R., Döpke, D., 2018, Peri-Gondwanan Ordovician arc magmatism in southeastern Ireland and the Isle of Man: Constraints on the timing of Caledonian deformation in Ganderia: GSA Bulletin, v. 130 (11-12), p. 1918-1939.

Gallagher, V., 1989, The occurrence, textures, mineralogy and chemistry of a chromite-bearing serpentine, Cummer, Co. Wexford: Geological Survey of Ireland Bulletin, v. 4(2), p. 89-98.

Gallagher, V., O'Connor, P.J. and Aftalion, M., 1994, Intra-Ordovician deformation in southeast Ireland: evidence from the geological setting, geochemical affinities and U-Pb zircon age of the Croghan Kinshelagh granite: Geological Magazine, v. 131, p. 669-684.

Gammons, C.H. and Williams-Jones, A.E., 1995, Hydrothermal geochemistry of electrum: Thermodynamic constraints: ECONOMIC GEOLOGY, v. 90, p. 420-432.

Geological Survey of Ireland, 2000, 'Gold smoke!' Minerals Section leaflet on South-East Leinster, 2 p.

Groen, J.C., Craig, J.R. and Rimstidt, J.D., 1990, Gold–rich rim formation on electrum grains in placers: Canadian Mineralogist, v. 28, p. 207-228.

Hough, R.M., Butt, C.R.M. and Fischer-Buhner, J., 2009, The crystallography, metallography and composition of gold: Elements, v.5, p297-302.

Huston, D., 2000, Gold in volcanic-hosted massive sulphide deposits; distribution, genesis and exploration: Gold in 2000, SEG Reviews, v. 13, p. 401-426.

IMC Exploration PLC, 2013, Boley-Kilmichael Gold Project, County Wexford, Ireland: presentation available from company website http://imcexploration.com/images/Wexford-Project.pdf.

Ixer, R.A., McArdle, P. and Stanley, C.J., 1990, Primary gold mineralization within metamorphosed iron ores, Southeast Ireland: Geological Survey of Ireland Bulletin, v. 4, p. 221-226.

Kennan, P.S., McArdle, P., Williams, F.M. and Doyle, E., 1986, A review of metal deposits associated with the Leinster granite, SE Ireland and a model for their genesis, in Andrew, C.J. et al., eds., Geology and genesis of mineral deposits in Ireland: Irish Association for Economic Geology, p. 201-210.

Kinahan, G.A., 1882, On the mode of occurrence and winning of gold in Ireland: Scientific Proceedings of the Royal Dublin Society, v. 3, p. 263-285.

Kinahan, G.H. 1883, On the possibility of gold being found in quantity in the County Wicklow: Scientific Proceedings of the Royal Dublin Society, v. 4, p. 39-42.

Knight, J., Coxon, P., McCabe, A.M. and McCarron, S.G., 2004, Pleistocene glaciations in Ireland: Developments in Quaternary Sciences, v. 2, p. 183-191.

Knights, K.V. and Heath, P.J., 2016, Quality control and statistical summaries of Tellus stream sediment regional geochemical data: analytical data 2016: Geological Survey of Ireland, 252 p.

Leake, R.C., Chapman, R.J., Bland, D.J., Condliffe, E. and Styles, M.T., 1997, Microchemical characterization of gold from Scotland: Transactions of the Institution of Mining and Metallurgy (Section B Applied Earth Sciences), v. 106, p. 85-98.

Leake, R.C., Chapman, R.J., Bland, D.J., Stone, P., Cameron, D.G. and Styles, M.T., 1998, The origin of alluvial gold in the Leadhills area of Scotland: evidence from interpretation of internal chemical characteristics: Journal of Geochemical Exploration, v. 63, p.7-36.

Lyburn, E. St John., 1901, Prospecting for gold in County Wicklow and an examination of Irish rocks for gold and silver: Scientific Proceedings of the Royal Dublin Society, v.9, p. 422-433.

Maclaren, M.J., 1903, The occurrence of gold in Great Britain and Ireland: Transactions of the Institute of Mining Engineers, v. 25, p. 435-508.

Malone, J., 2007, The rivers of southeast Ireland and the sands of the Irish Sea: heavy minerals show that proximity does not always predetermine provenance, in Mange, M.A. and Wright, D.T., eds., Heavy minerals in use: Developments in Sedimentology, v. 58, p. 547-568.

McArdle, P., 1993, Evolution and preservation of volcanogenic sulphides at Avoca, southeast Ireland: Transactions of the Institution of Mining and Metallurgy, Section B: Applied Earth Science, v. 102, p. 149-163.

McArdle, P. and Warren, W.P., 1987a, The bedrock source and emplacement of placer gold at Goldmine River valley, County Wicklow: Geological Survey of Ireland Bulletin, v. 4, p. 11-26.

McArdle, P. and Warren, W.P., 1987b, Iron formation as a bedrock source of gold in southeast Ireland and its implications for exploration: Transactions of the Institution of Mining and Metallurgy (Section B Applied Earth Sciences), v. 96, p. 195-200.

McArdle, P., Fitzell, M., Oosterom, M.G., O'Connor, P.J. and Kennan, P.S., 1989, Tourmalinite as a potential host rock for gold in the Caledonides of Southeast Ireland: Mineralium Deposita, v. 24, p. 154-159.

McClenaghan, M.B., 2011, Overview of common processing methods for recovery of indicator minerals from sediment and bedrock in mineral exploration: Geochemistry, exploration, Environment, Analysis, v.11 p. 251-263.

McClenaghan, M.B. and Paulen, R.C., 2018, Application of till mineralogy and geochemistry to mineral exploration, in Menzies, J. and van der Meer, J.J.M., eds., Past glacial environments, 2nd edition, p. 689-751.

McKillen, Tyler and Associates, 2009, Surrender Report, Minco Ireland Limited Prospecting Licences 2239 and 3857, County Wicklow: Exploration and Mining Division, Department of Communications, Energy and Natural Resources, Government of Ireland, Open File report, 7 p.

Milner, A.L. and McArdle, P., 1992, Gold mineralization in Ordovician volcanic rocks at Kilmacoo, County Wicklow: its exploration and geological controls, in Bowden, A.A., Earls, G., O’Connor, P.G. and Pyne, J.F., eds., The Irish Minerals Industry 1980–1990, Irish Association for Economic Geology, p. 51-63.

Moles, N.R., Chapman, R.J., and Warner, R.B., 2013, The significance of copper concentrations in natural gold alloy for reconnaissance exploration and understanding gold-depositing hydrothermal systems: Geochemistry, Exploration, Environment, Analysis, v. 13, p. 115-130.

Moon, C.J. and Hale, M., 1983, Geochemical dispersion patterns of As, Sb, Bi and Se associated with sulfide mineralization at Avoca, Eire. Journal of Geochemical Exploration, v. 19, p. 663-677.

Nakashole, A.N., Hodgson, D.M., Chapman, R.J., Morgan, D.J. and Jacob, R.J., 2018, Long-term controls on continental-scale bedrock river terrace deposition from integrated clast and heavy mineral assemblage analysis: An example from the lower Orange River, Namibia: Sedimentary Geology, v. 364, p. 103-120.

O'Brien, M.V., 1959, The future of non-ferrous mining in Ireland, in The future of non-ferrous mining in Great Britain and Ireland, Institution of Mining and Metallurgy, London, p. 5-26.

O'Connor, P.J. and Brück, P.M., 1978, Age and origin of the Leinster Granite: Royal Irish Academy Journal of Earth Sciences, v. 1(2), p. 105-113.

O’Connor, P.J. and Gallagher, V., 1994, Gold prospectivity in the Caledonides of southeast Ireland: application of the upper crustal reservoir model: Transactions of the Institution of Mining and Metallurgy (Section B Applied Earth Sciences), v. 103, p. 175-187.

O'Connor, P.J., and Reimann, C., 1993, Multi-element regional geochemical reconnaissance as an aid to target selection in Irish Caledonian terrains: Journal of Geochemical Exploration, v. 47, p. 63-89.

Reeves, T.J., 1971, Gold in Ireland: Geological Survey of Ireland Bulletin, v. 1, p. 73-85.

Riofinex North Limited, 1993 and 1994, Work reports for Prospecting Licence 1545, County Wicklow: Geological Survey of Ireland (GSI) open file reports.

Sheppard, W.A., 1980, The ores and host rock geology of the Avoca Mines, Co. Wicklow: Norges. Geol. Undersokelse, v. 57, p. 269-284.

Smyth, D., 2007, Methods used in the Tellus geochemical mapping of Northern Ireland: British Geological Survey Technical Report OR/07/022.

Smyth, W.W., 1853, On the mines of Wicklow and Wexford: Records of the School of Mines, 1, 349-412.

Standish, C.D., Dhuime, B., Chapman, R.J., Hawkesworth, C.J. and Pike, A.W.G., 2014, The genesis of gold mineralisation hosted by orogenic belts: a lead isotope investigation of Irish gold deposits: Chemical Geology, v. 378-379, p. 40-51.

Steiger, R. and Bowden, A., 1982, Tungsten mineralization in southeast Leinster, Ireland, in Brown, A.G. ed., Mineral exploration in Ireland, progress and development 1971-1981, Irish Association for Economic Geology, p. 108-114.

Tietzsch-Tyler, D., Sleeman, A.G., McConnell, B.J., Daly, E.P., Flegg, A.M., O’Connor, P.J. and Warren, W.P., 1994, Geology of Carlow – Wexford: A geological description to accompany the bedrock geology 1:100,000 map series, sheet 19, Carlow–Wexford: Geological Survey of Ireland.

Warren, W.P., 1993, Wicklow in the Ice Age: Geological Survey of Ireland, Dublin, 46 p.

Weaver, T., 1835, On the gold-workings formerly conducted in the County of Wicklow, Ireland: Philosophical Magazine and Journal of Science, 3rd Series, v. 7, p. B1-B6.

Wheatley, C.J.V., 1971, Economic geology of the Avoca mineralised belt, S.E. Ireland and Parys Mountain, Anglesey: Unpublished Ph.D. thesis, Imperial College, London.

Williams, F.M., Sheppard, W.A. and McArdle, P., 1986, Avoca Mine, County Wicklow: A review of geological and isotopic studies, in Bowden, A.A., Earls, G., O’Connor, P.G. and Pyne, J.F., eds., The Irish Minerals Industry 1980–1990, Irish Association for Economic Geology, p. 71-82.

Figures (placed in Publisher / PDF file)

FIG. 1. SE Ireland map with outlines of the Ribband and Duncannon Groups and the Leinster Granite, locating the main towns and study area map shown in Fig. 2 (red dashed boxes indicate the main map area and the Ennicorthy inset map). Inset reproduced with permission from the Geological Survey of Ireland: map of interpolated Au in Tellus sediments in SE Ireland showing an area of relatively high values in north-central Wexford and scattered high values in Wicklow and Carlow; small map shows map location within Ireland.

FIG. 2. Geologic map of the North Wexford – South Wicklow study area (after Tietzsch-Tyler et al., 1994) with occurrences of detrital gold and various styles of bedrock mineralization based on O'Connor and Gallagher (1994) and exploration company reports (see Table 1 for sources). Blue arrows indicate ice flow directions during previous glaciations (Warren, 1993). Star symbols are sample locations in this study, letters designate Wicklow sites and numbers designate Wexford sites: refer to Table 2 for locality names. Dotted black line is the N11/M11 highway. Green box is the area of Fig. 3.

FIG. 3. Topographic and geologic map of the Goldmines River area with sample locations and features referred to in the text. Weaver's trenches are excavations through overburden to bedrock instigated by Thomas Weaver (1835). Red stippling indicates river sections that were worked historically for placer gold (after Reeves 1971) implying relatively high abundances. Star symbols are sample locations in this study (Table 2).

FIG. 4. Ag distributions in detrital gold samples underpinning approaches to data interpretation used in this study. A: reproducibility of Ag contents of samples obtained from two locations sampled on different occasions. B: all Wexford samples, showing a common plot form and providing justification for locality definition using a single statistical measure (median %Ag). C: cumulative plot of median %Ag values for the 46 samples from the study area in which 4 or more gold grains were obtained, with 'low' to 'high' categories defined (data in Table 2). D: selected Wicklow samples showing wide variation in plot form (details in Fig. 9).

FIG. 5. Pie charts of heavy mineral proportions in panned concentrates from sample sites on an outline geology map of the study area. Inset map at the same scale shows the Adamstown area; for location refer to Fig. 1. Locality names and data in Table 3.

FIG. 6. Outline geology of the study area (refer to key in Fig. 2) with symbols at sample sites indicating (A) detrital gold abundance, with 'high*' indicating concentration of detrital gold previously sufficiently high to support historical exploitation, and (B) median %Ag categories at sites from which 4 or more gold grains were obtained (Table 2 and Fig. 4 C).

FIG. 7. Morphology and size of gold grains from selected sites in Wexford and Wicklow. Scale bars 1mm. A: Nuggets to 1g from Monaglogh River. B: Rough gold to 0.5g showing morphology consistent with limited transport, from Ballinvally River sampled near the Red Hole. C: Relatively waterworn gold from Milshoge, Wexford.

FIG. 8. Examples of microtextures revealed in polished sections of detrital gold grains. A, B: typical examples of arsenopyrite and galena inclusions observed in gold from throughout the study area. C: native bismuth and galena inclusions in gold from Monaglogh River. D: typical homogenous Au alloy of gold grains from the Monaglogh and Ballinvally Rivers. E, F: examples of alloy heterogeneity frequently observed in gold grains from Wexford.

FIG. 9. Characteristics of gold populations in Wicklow indicated by variation in Ag signatures in the Wicklow sample sites. A: Definition of gold types 1 and 2 according to Ag range of Pb-Bi

association and As-Pb association (horizontal line). B: Sample localities north of Croghan Kinshelagh. C and D: Comparison of samples from within the catchments of the Ballinvally and Monaglogh Rivers respectively.

FIG. 10. Depiction of inclusion assemblages. Mineral abbreviations as in Table 2. Additional abbreviations: Hs = hessite, Cl = clausthalite. A: Comparison of gold types 1–3, Wicklow region. B: Comparison of inclusion signatures of gold hosted in the Duncannon and Ribband Groups, Wexford. C: Inclusion assemblages of Wexford sites that have atypical heavy mineral concentrates (Askamore, Boley) compared with other Ribband Group localities.

FIG. 11 A-J. Study area outline geology (refer to key in Fig. 2) with Tellus fine fraction stream sediment sample geochemical data for Au, Bi, Pb, Cu, As, Sb, Cr, Ni, Sn, and W. Inset map at the same scale shows the Adamstown area (for location refer to Fig. 1).

FIG. 12. Outline map of south Wicklow showing historical placer workings, zones of stratabound Au-As-Fe-S mineralization, and proposed bedrock sources and transport processes affecting placer gold accumulations. Catchment areas are colour-coded according to the proportions of hematite, magnetite and ilmenite in HMC samples with opacity in proportion to abundance of these components (data in Table 3). Pie charts show the proportions of gold types 1-3 in each main area (data in Table 4).

Tables (placed at end of this manuscript and also available as individual Word and Excel files)

TABLE 1. Summary of auriferous bedrock mineralization reported in the southeast Ireland study area, excluding the Avoca and Kilmacoo ore deposits. Localities are shown in Fig. 2. Sources: 1: Milner and McArdle (1992). 2: Shepherd (1980) and Williams et al. (1986). 3: McArdle (1993). 4: Ixer et al. (1990). 5: Downes and Platt 1978. 6: McArdle and Warren (1987a, b). 7: McKillen, Tyler and Associates (2009). 8: Dana Exploration PLC (1992). 9: Riofinex North Limited (1993 and 1994). 10: McKillen, Tyler and Associates (2009). 11: Kennan et al. (1986) and Steiger and Bowden (1982). 12: Geological Survey of Ireland (2000). 13: IMC Exploration PLC (2013).

TABLE 2. Sample locality names and codes (numbers indicate Wicklow, letters indicate Wexford), detrital gold abundance, median % Ag in gold alloy, and inclusion assemblages. Mineral abbreviations: Py = pyrite, Po = pyrrhotite, Gn = galena, Cpy = chalcopyrite, Sph = sphalerite, CuSbS = chalcostibite, Ars = arsenopyrite, Grs = gersdorffite and similar FeNi(Co)AsS minerals, Alt = altaite, Bi = native bismuth. Duplicate samples indicated by boxed rows, with inclusion species tallied in the two samples. ^ indicates sites sampled in 2013 by Christopher Reynolds and Christopher Smith. High* indicates concentration of detrital gold previously sufficiently high to support historical exploitation.

TABLE 3. Percentages (volume %) of minerals in heavy mineral concentrates from sample sites in the study area.

TABLE 4. Characteristics of detrital gold types 1–3 in the Goldmines River area (Wicklow) and the proportions of each type at sites where a sufficient number of grains was recovered to permit microchemical characterization.

TABLE 1 (Word file)

County	Locality	Setting/description/mineralogy	Gold grade/concentration / composition	Comments
Wicklow	Kilmacoo	Orogenic remobilisation of gold precipitated in sulfide-rich, silicified chloritic tuffs[1]	Riofinex best intersection 30 m at 4.4 g/T. Gold within sulfides typically <10 micron, gold within quartz veins typically ~20 micron[1]	Tabular zone 30 m thick by >150 m along strike. Considered to have formed by preferential deposition of Au in veined/sheared rock[1]
	Avoca	Kuroko style Volcanogenic Massive Sulfide deposit[2,3]	Typically <10 micron grains, 12-15% Ag[2]	Historically mined, sub-economic resource remains[3]
	Ballycoog–Moneyteige Ridge	Banded Iron Formation containing siderite and magnetite with minor (<1%) sulphides[4-6]	Native Au hosted in sulfides contains 17% Ag (2 analyses)[4]	Considered to be a exhalative equivalent of the Avoca volcanogenic sulphide deposits[5,6]
	Maclaren Zone, Monaglogh River	Stratabound Au-As-Fe-S comprising veins and disseminations of pyrite and arsenopyrite hosted in chloritic, sericitic and felsic tuffs[7,8,9]	Road cut exposes 1.3 m with 3 g/T Au. Up to 12.55 g/T Au in rock chip samples[10]	
	Mary Ellen Zone, Ballinvally River		GSI borehole 94/2 included 2.2 m at 1 g/t Au[6]. Trenching included 3 m at 1.28 g/T with grab samples containing 3.45 to 42.5 g/T Au[7,8,9,10]	20 m thick Au-enriched stratabound zone extending >400 m along strike at contact between Ribband and Duncannon Groups[7,8,9]
	West Slievefoore Zone			60 m thick Au-enriched stratabound zone extending along strike for >3 km[8]
	Kingston and Killshelagh	Chalcopyrite-bearing quartz veins enriched in As, Au and Ag	Up to 0.45 g/T Au in pyritic breccia[8]	Outcropping mineralization considered to be part of a swarm of Au-As-Fe-S veins[8]
	Croghan Complex	Granite-hosted Sn-W-Au greisen	'Low grade'[8]	
	Ballinglen	W-Sn mineralization in greisenized albitic microtonalite sheets. Stage 1: scheelite, arsenopyrite, pyrrhotite. Stage 2: sphalerite, galena, chalcopyrite, pyrite, stannite, cassiterite.[11]	Bi-Mo-Au enrichment noted	Main locality near Ballinglen is part of an extensive weakly mineralized zone (Fig. 2)
Wexford	Kilmichael-Ballyowen-Ballygarrett	Au-As-Fe-S mineralization in tuffs	Borehole 13.5 m intercept at 3.5 g/T Au, including 0.7m at 10 g/T Au. Trench sample 30 m at 0.38 g/T plus 3 m at 3.6 g/T[7]. Float to 980 g/T[12,13]	Potential mineralized zone of 6.5 km in strike length reported by IMC in 2013[11]
	Boley	Oakland Formation phyllites with auriferous quartz veins	1.5 m intercept at 354 g/T Au within 13.5 m averaging 3.5 g/T[13]	Proposed structural control at intersection of ENE trending fractures and regional strike[13]
	Craan Hill - Knockbrandon	Auriferous quartz veins and sulfide mineralization	0.25 m intercept at 9.6 g/T Au. Quartz float to 18 g/T, 'mineralized boulders' to 32 g/T[12,13]	
	Tombreen	Stratabound Au-As-Fe-S mineralization in sheared felsic tuffs and phyllites	Intercepts of 0.38 m at 11.65 g/T, 0.5m at 18.4 g/T. Float to 286 g/T[12,13]	Close to mapped contact of the Maulin and Ballylane formations
	Knocknalour	Stratabound Au-As-S mineralization in sheared felsic tuffs and phyllites	Borehole intercepts 0.4 m at 19.9 g/T Au, 0.3 m at 10.45 g/T Au[12,13]	
	Churchtown	Au-As-Fe-S mineralization hosted by rhyolite in a shear zone	Borehole intercept 8m at 0.2 g/T Au[12]	

TABLE 2 (Excel file)

Map code	Site / river name	County	Irish Grid ref.	Abundance	Number of grains	Median %Ag	Median %Ag category	No. grains with inc.	% with inc.	Total no. inclusions	Metalliferous inclusion species: Py	Po	Gn	Cpy	Sph	CuSbS	Ars	Grs	Alt	Bi	Others
1	Kilmacoo north	Wicklow	T 211 850	very low	2	-	-	0	0	0											
2	Knockanode	Wicklow	T 193 823	very low	4	3.7	low	1	25	2			1								Native As
3	Avoca tributary	Wicklow	T 214 819	low	33	8.0	high	6	18	7	1		1	1		1	3				
4	Ow River	Wicklow	T 111 800	low	19	3.4	low	6	32	8	1	1	4	2							
5	Castlemacadam	Wicklow	T 194 792	very low	4	3.4	low	0	0	0											
6	Clone stream	Wicklow	T 140 785	high*	62	3.6	low	5	8	6			9	2	1						
6	Clone stream	Wicklow	T 140 785	high*	51	4.0	low	5	10	6											
7	Ballintemple stream	Wicklow	T 177 780	high*	62	3.9	low	9	15	11	3		1	1			3		2		Wittichenite
8	Tomnaskela River	Wicklow	T 105 738	very low	2	-	-	0	0	0											
9	Coolbawn River	Wicklow	T 132 750	high*	46	11.5	high	3	7	3			3								
10	Ballinvally River trib., Ballykillageer	Wicklow	T 165 761	low	13	6.5	medium	1	8	1			1								
11	Ballinvally River, Red Hole	Wicklow	T 160 745	high*	81	8.5	high	16	19	22	5		5	1			5	1		2	Plumbogummite x3
12	Ballinvally River upper, Ballinagore	Wicklow	T 152 742	low	25	9.5	high	3	8	3	1			1							Tsumoite
13	Monaglogh R trib., Rostygah	Wicklow	T 182 754	high*	68	6.2	medium	15	22	17	3		9	1			2	1			Unidentified CuAsS
14	Monaglogh River	Wicklow	T 180 745	high*	60	8.4	high	6	10	8	4	1	7	1		1	4	1		1	
14	Monaglogh R duplicates 2 & 3	Wicklow	T 178 747	high*	73	8.3	high	9	12	12											
15	Monaglogh tributary	Wicklow	T 180 750	low	21	3.3	low	3	14	3							2	1			
16	Monaglogh R upper, Killahurler	Wicklow	T 174 737	very low	5	7.2	medium	0	0	0											
A	Kilcloran	Wexford	T 054 533	low	46	6.2	medium	3	7	3	2		1								
B	Hyde Park	Wexford	T 208 665	medium	81	5.7	medium	9	11	11	2		4			4	1				
C	Cullenoge	Wexford	T 207 647	low	50	5.0	low	5	10	12	4		2	3			2	1			
D	Coolnacon Bridge	Wexford	S 839 307	medium	91	3.2	low	8	9	8	2		1	3	1		1				
E	Misterin	Wexford	S 842 264	very low	13	3.8	low	1	8	1								1			
F	Ballyshannon	Wexford	S 850 255	low	48	4.4	low	2	4	3	1							2			
G	Boley Lower	Wexford	T 069 562	high	192	5.9	medium	17	9	24	4		6	3	1	5	5				
H	Rossminoge South	Wexford	T 069 576	very low	20	5.0	low	0	0	0											
I	Ballykale	Wexford	T 160 563	high	167	7.5	medium	13	8	19	4	1	3	3			7	1			
J	Newbridge Wood	Wexford	T 060 558	low	21	4.8	low	1	5	1							1				
K	Askamore Burn	Wexford	T 025 585	low	30	6.5	medium	4	13	4	1			1			1		2		Clausthalite
K	Askamore duplicate	Wexford	T 024 583	low	30	5.8	medium	2	7	2											
L	Milshoge	Wexford	T 065 520	high	96	7.3	medium	3	3	4	1			1			2				
M	Knockrobin Lower	Wexford	T 082 516	low	18	5.2	low	1	6	1							1				
N	Ballyeden	Wexford	T 099 517	low	68	6.3	medium	6	9	5	2	1					2				
Q	Huntingtown	Wexford	T 110 574	low	41	8.3	high	5	8	5	3					1	1				
R	Ballygarrett (Ballyowen)	Wexford	T 105 596	high	64	7.9	high	2	3	2	3		1		1	1	2				
R	Ballygarrett duplicate^	Wexford	T 115 607	high	114	7.5	medium	6	5	6											
S	Gibbett Hill	Wexford	S 961 576	medium	55	5.9	medium	3	5	3	1		1				1				
T1	Tombreen 1	straddle	T 003 622	low	30	7.4	medium	2	7	2			2	1			2	1			
T2	Tombreen 2	straddle	S 987 619	low	28	5.3	low	3	11	4											
V	River Bann, Holyfort	Wexford	T 122 641	very low	3	3.9	-	0	0	0											
W	S. Corbetstown^	Wexford	T 067 487	high	93	6.6	medium	3	3	3	3										
X	Coolnaveagh^	Wexford	T 146 573	medium	57	6.4	medium	4	7	5	1					1	1	1			Cobaltite
Y	Kilmichael^	Wexford	T 114 625	medium	30	7.0	medium	2	7	2	1			1							
Z	Ballyduff^	Wexford	T 115 502	medium	43	7.1	medium	5	12	8	1				1	1	3	1			Boulangerite
				Total:	2160			198		**247**	54	4	62	26	5	15	52	12	4	3	10

TABLE 3 (Excel file)

Site code	Site / river name	Barite	Hematite	Magnetite	Ilmenite	Rutile	Chrome spinel	Cassiterite	Ferberite	Tantalite	Monazite	Zircon	Garnet	Staurolite
1	Kilmacoo north	-	13	-	-	-	-	-	-	-	-	-	75	12
2	Knockanode	-	8	-	-	-	-	-	-	-	-	-	80	12
3	Avoca tributary	-	-	-	-	-	-	-	-	-	-	-	86	14
4	Ow River	-	-	-	-	-	-	-	-	-	-	-	85	15
5	Castlemacadam	-	27	-	10	-	-	-	-	-	-	-	42	21
6	Clone stream	-	-	-	5	-	2	5	2	-	-	-	68	18
7	Ballintemple stream	-	11	2	5	-	2	9	-	-	-	-	56	15
8	Tomnaskela River	-	-	-	75	-	3	6	2	-	-	2	12	-
9	Coolbawn River	-	20	37	30	-	-	-	5	-	-	-	8	-
9n	Moneyteige North	-	18	11	25	-	3	9	3	-	2	-	22	7
11	Ballinvally River, Red Hole	-	16	32	42	-	-	-	-	-	-	-	10	-
13	Monaglogh R trib., Rostygah	-	40	4	2	-	-	4	2	-	-	-	33	15
14	Monaglogh River	-	4	19	40	10	-	3	-	-	-	-	19	5
A	Kilcloran	-	11	-	50	-	-	2	2	-	16	3	16	-
B	Hyde Park	-	12	-	38	-	-	4	2	-	3	-	41	-
C	Cullenoge	-	15	-	55	-	-	-	-	-	-	8	22	-
D	Coolnacon Bridge	-	-	5	60	4	-	5	-	-	-	-	17	9
E	Misterin	-	-	5	68	6	-	2	-	-	-	-	13	6
F	BallyShannon	-	-	-	57	4	-	7	-	1	2	-	17	12
G	Boley Lower	-	9	-	7	-	3	17	19	2	29	-	14	-
H	Rossminogue south	-	-	-	39	-	10	5	-	-	20	2	24	-
I	Ballykale	-	8	-	39	-	12	4	2	1	-	2	32	-
J	Newbridge Wood	-	-	-	66	-	-	4	-	-	16	-	14	-
K	Askamore	-	-	-	5	-	-	54	10	4	3	-	24	-
L	Milshoge	-	9	-	54	9	-	12	-	-	10	-	6	-
M	Knockrobin Lower	-	7	-	60	6	-	-	-	-	-	-	27	-
N	Ballyeden	-	11	-	45	3	-	3	-	-	-	4	34	-
P	Bolinready	-	9	-	39	-	-	-	-	-	-	-	52	-
Q	Huntingstown	-	3	-	67	-	6	3	-	-	-	3	18	-
R	Ballygarrett / Ballyowen	13	6	-	21	-	21	9	3	-	18	-	9	-

TABLE 4 (Word file)

Type	**1**	**2**	**3**
%Ag range in alloy	0 – 9	9 – 15	>15
Defining inclusion mineralogy	Galena ± native bismuth	galena, arsenopyrite	arsenopyrite
Locality	**% type 1**	**% type 2**	**% type 3**
Ballinvally River	43	51	6
Monaglogh River	47	20	33
Coolbawn River	20	65	15
Clone stream	73	24	3
Ballintemple stream	73	24	3
Ow River	90	9	1

Figures

Fig. 1

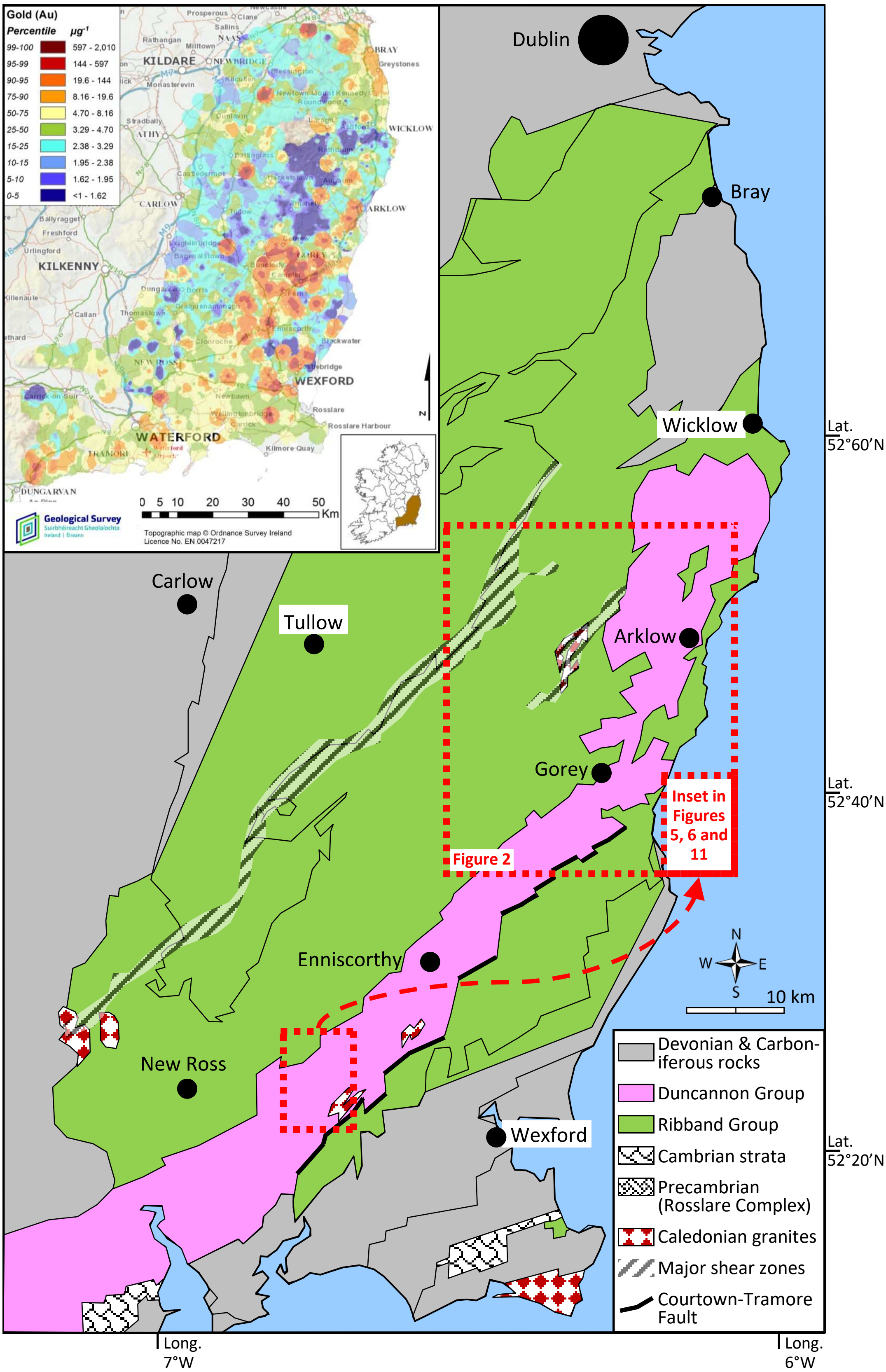
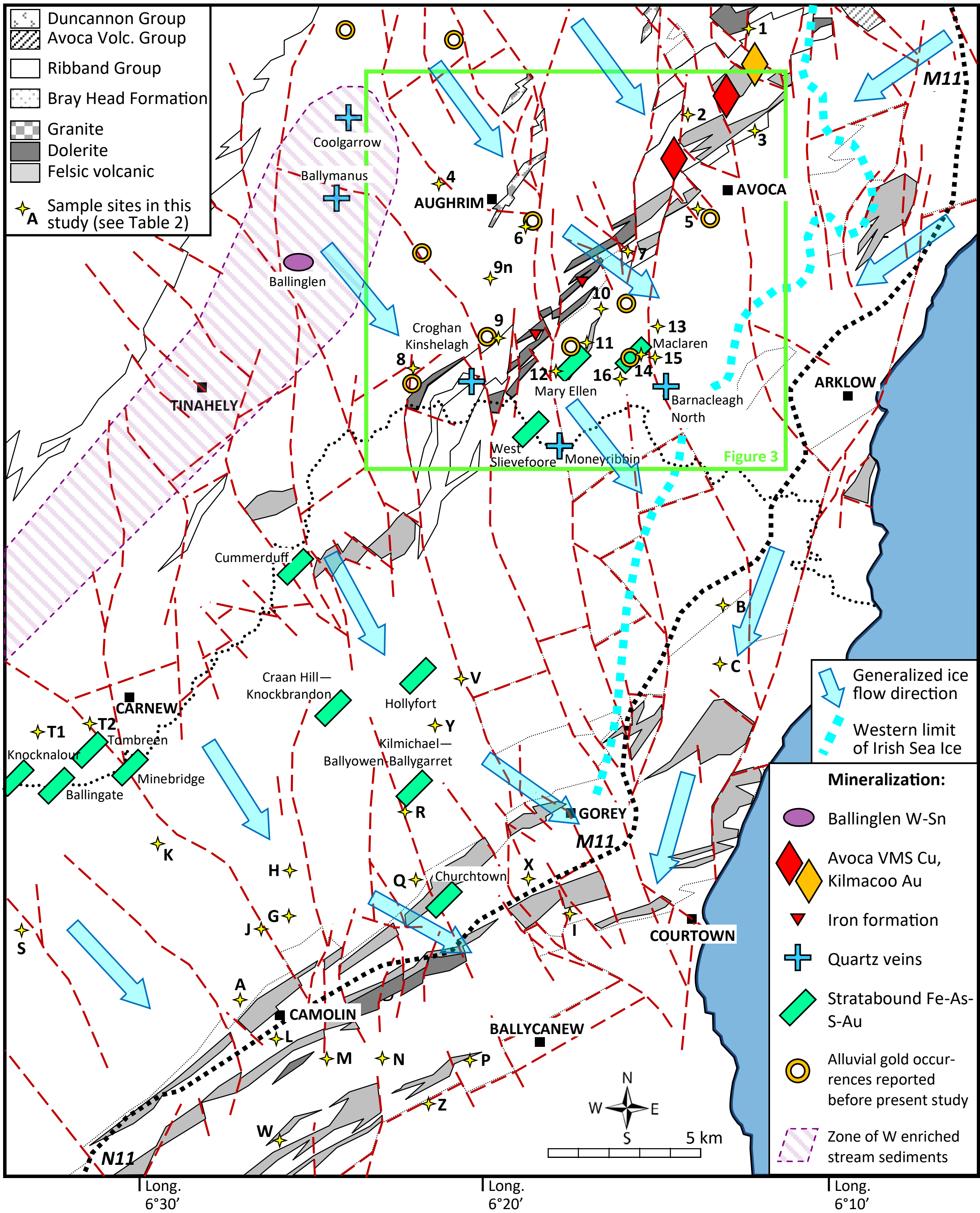
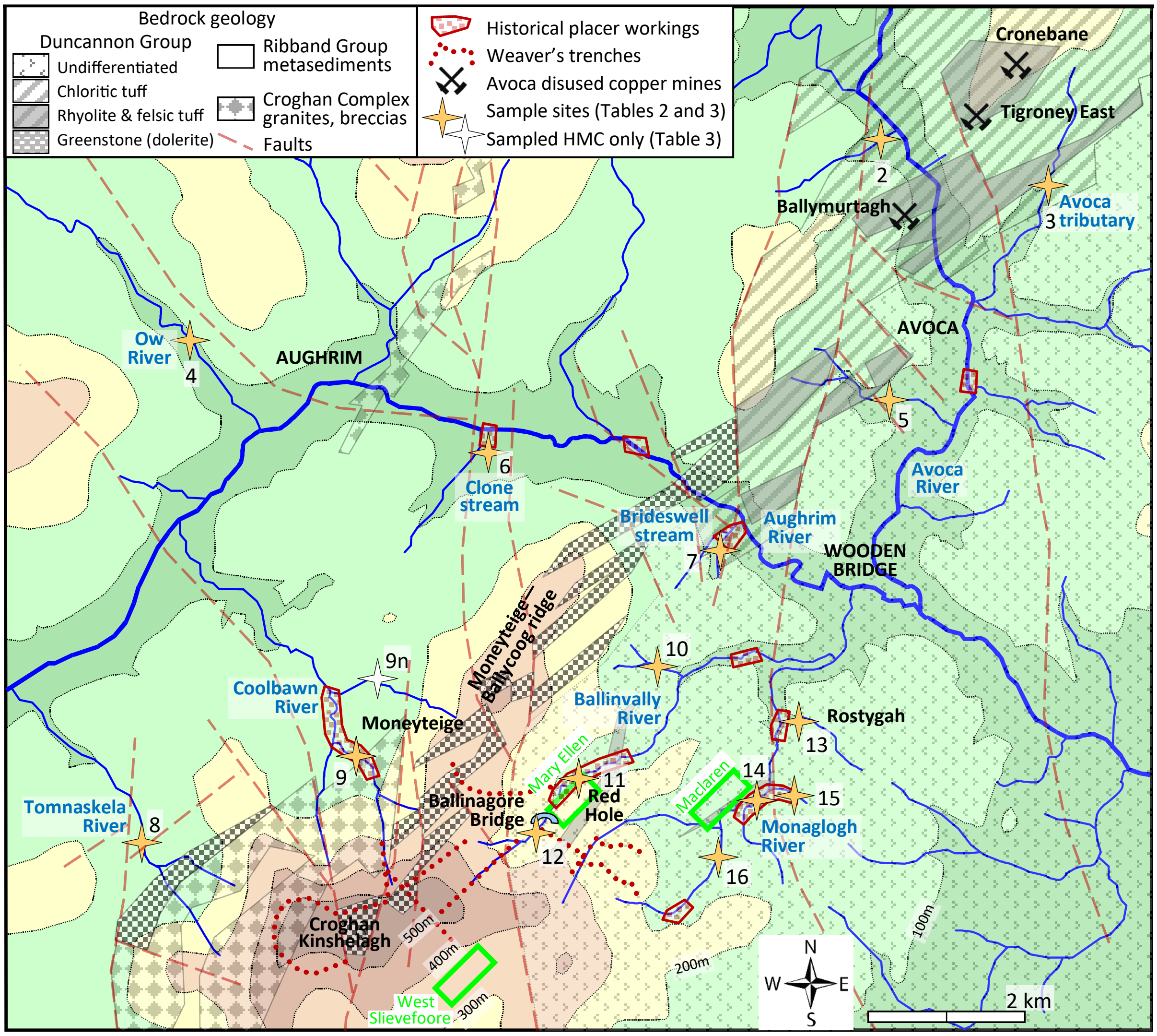


Fig. 2



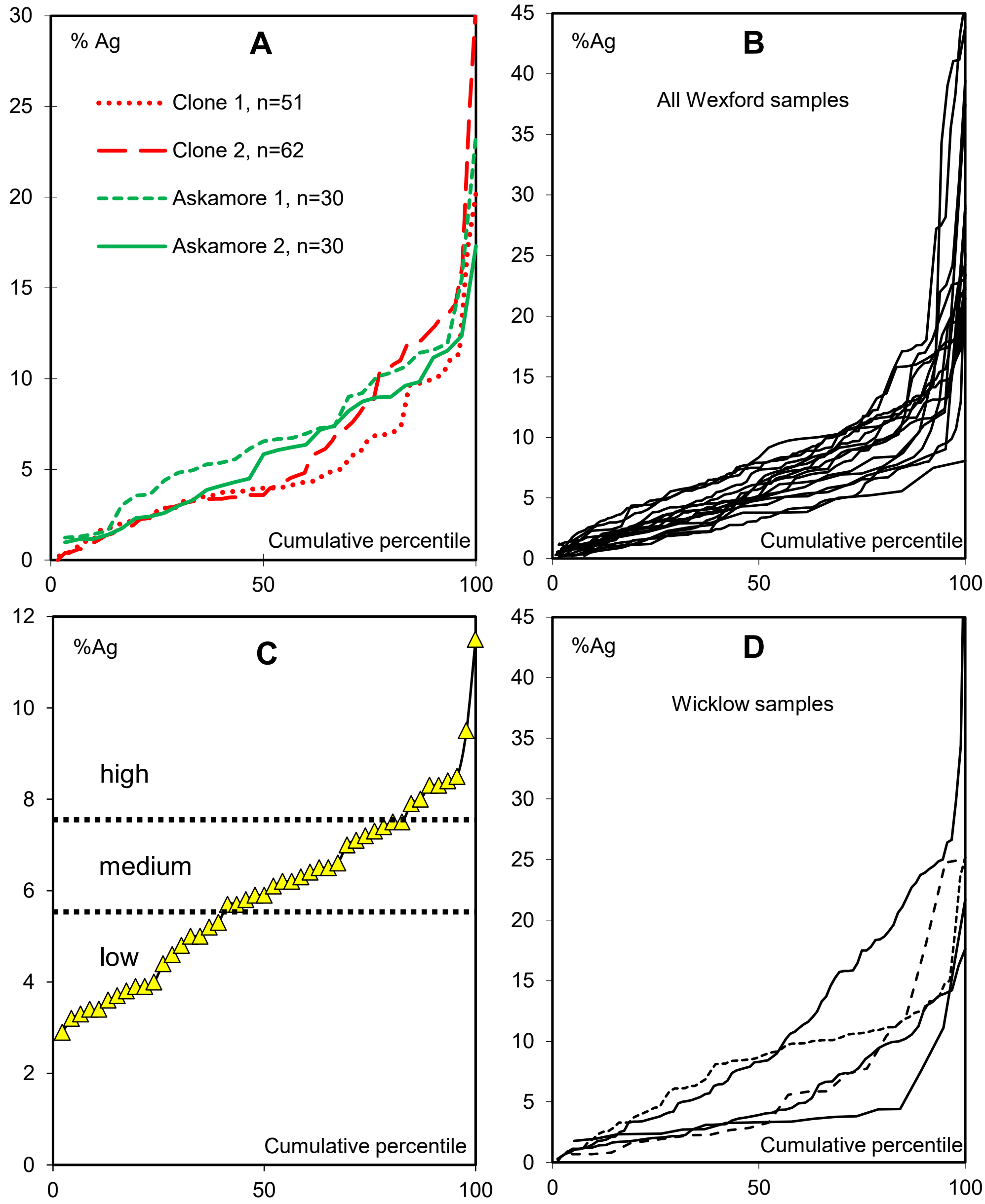
Duncannon Group
Avoca Volc. Group
Ribband Group
Bray Head Formation
Granite
Dolerite
Felsic volcanic
A Sample sites in this study (see Table 2)
Coolgarrow
Ballymanus
Ballinglen
TINAHELY
AUGHRIM
AVOCA
ARKLOW
Croghan Kinshelagh
Mary Ellen
Maclaren
Barnacleagh North
West Slievefoore
Moneyribbin
Figure 3
M11
Cummerduff
Craan Hill—Knockbrandon
Hollyfort
Kilmichael—Ballyowen-Ballygarret
CARNEW
Tombreen
Knocknalour
Minebridge
Ballingate
GOREY
Churchtown
COURTOWN
CAMOLIN
BALLYCANEW
N11
Generalized ice flow direction
Western limit of Irish Sea Ice
Mineralization:
Ballinglen W-Sn
Avoca VMS Cu, Kilmacoo Au
Iron formation
Quartz veins
Stratabound Fe-As-S-Au
Alluvial gold occurrences reported before present study
Zone of W enriched stream sediments
5 km
N
S
E
W
Lat. 52°50′
Lat. 52°40′
Long. 6°30′
Long. 6°20′
Long. 6°10′

Fig. 3



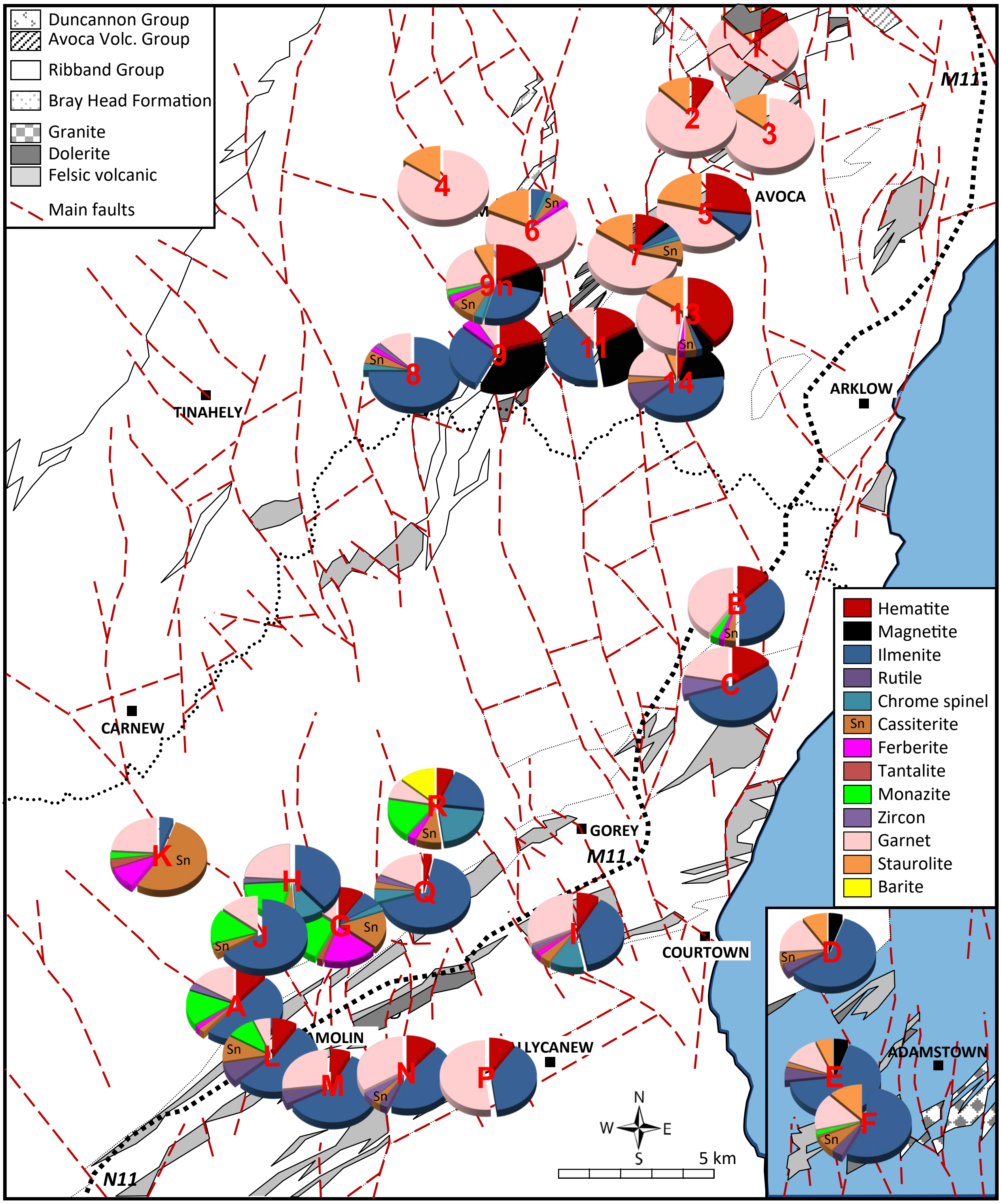
Bedrock geology
Duncannon Group
Undifferentiated
Chloritic tuff
Rhyolite & felsic tuff
Greenstone (dolerite)
Ribband Group metasediments
Croghan Complex granites, breccias
Faults
Historical placer workings
Weaver's trenches
Avoca disused copper mines
Sample sites (Tables 2 and 3)
Sampled HMC only (Table 3)
Cronebane
Tigroney East
Ballymurtagh
Avoca tributary
AVOCA
Ow River
AUGHRIM
Clone stream
Brideswell stream
Aughrim River
Avoca River
WOODEN BRIDGE
Moneyteige—Ballycoog ridge
Coolbawn River
Moneyteige
Ballinvally River
Rostygah
Tomnaskela River
Ballinagore Bridge
Mary Ellen
Red Hole
Maclaren
Monaglogh River
Croghan Kinshelagh
West Slievefoore
500m
400m
300m
200m
100m
2 km
N
W
E
S
2
3
4
5
6
7
8
9
9n
10
11
12
13
14
15
16

Fig. 4 A—D



A
% Ag
Clone 1, n=51
Clone 2, n=62
Askamore 1, n=30
Askamore 2, n=30
Cumulative percentile
B
%Ag
All Wexford samples
Cumulative percentile
C
%Ag
high
medium
low
Cumulative percentile
D
%Ag
Wicklow samples
Cumulative percentile

Fig. 5



Duncannon Group
Avoca Volc. Group
Ribband Group
Bray Head Formation
Granite
Dolerite
Felsic volcanic
Main faults
Hematite
Magnetite
Ilmenite
Rutile
Chrome spinel
Sn Cassiterite
Ferberite
Tantalite
Monazite
Zircon
Garnet
Staurolite
Barite
AVOCA
TINAHELY
ARKLOW
CARNEW
GOREY
M11
COURTOWN
ADAMSTOWN
N11
5 km
N
S
E
W

Fig. 6 A and B

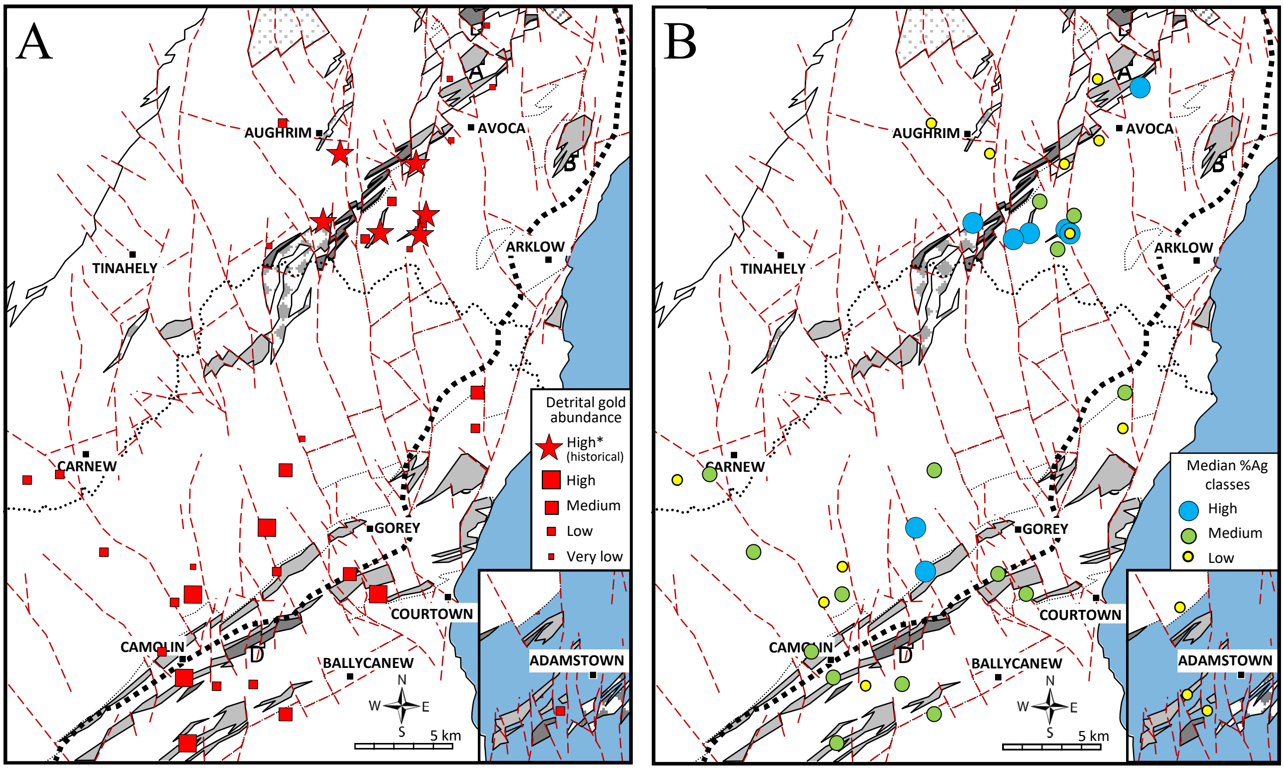

A
AUGHRIM
AVOCA
TINAHELY
ARKLOW
CARNEW
GOREY
COURTOWN
CAMOLIN
BALLYCANEW
ADAMSTOWN
Detrital gold abundance
High* (historical)
High
Medium
Low
Very low
5 km
B
AUGHRIM
AVOCA
TINAHELY
ARKLOW
CARNEW
GOREY
COURTOWN
BALLYCANEW
ADAMSTOWN
Median %Ag classes
High
Medium
Low
5 km

Fig. 7 A—C

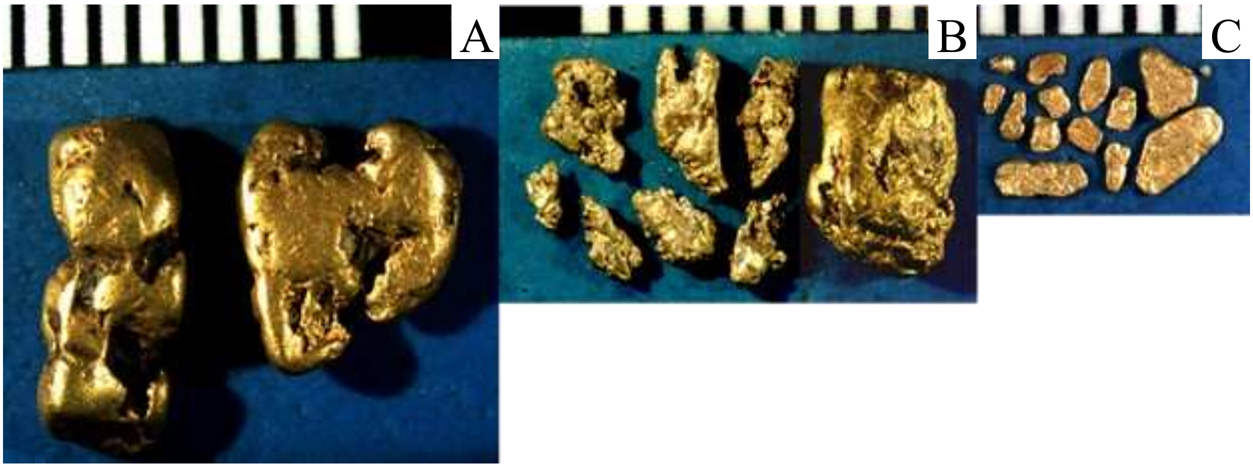


Fig. 8 A—F

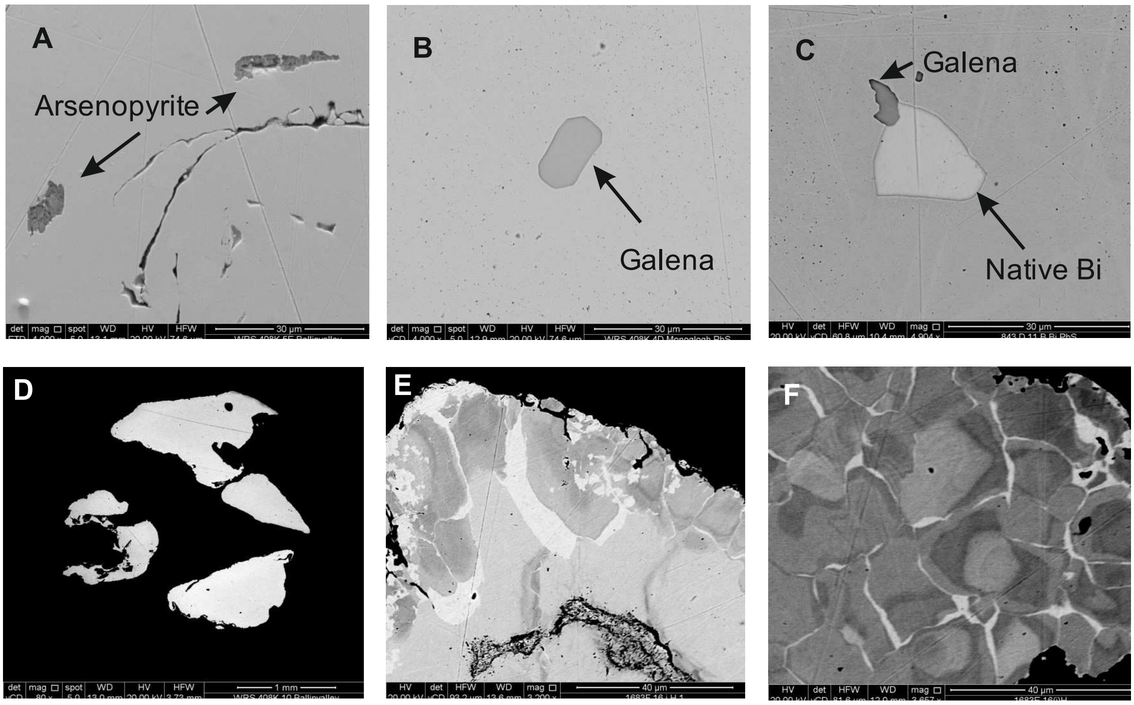


Fig. 9 A–D

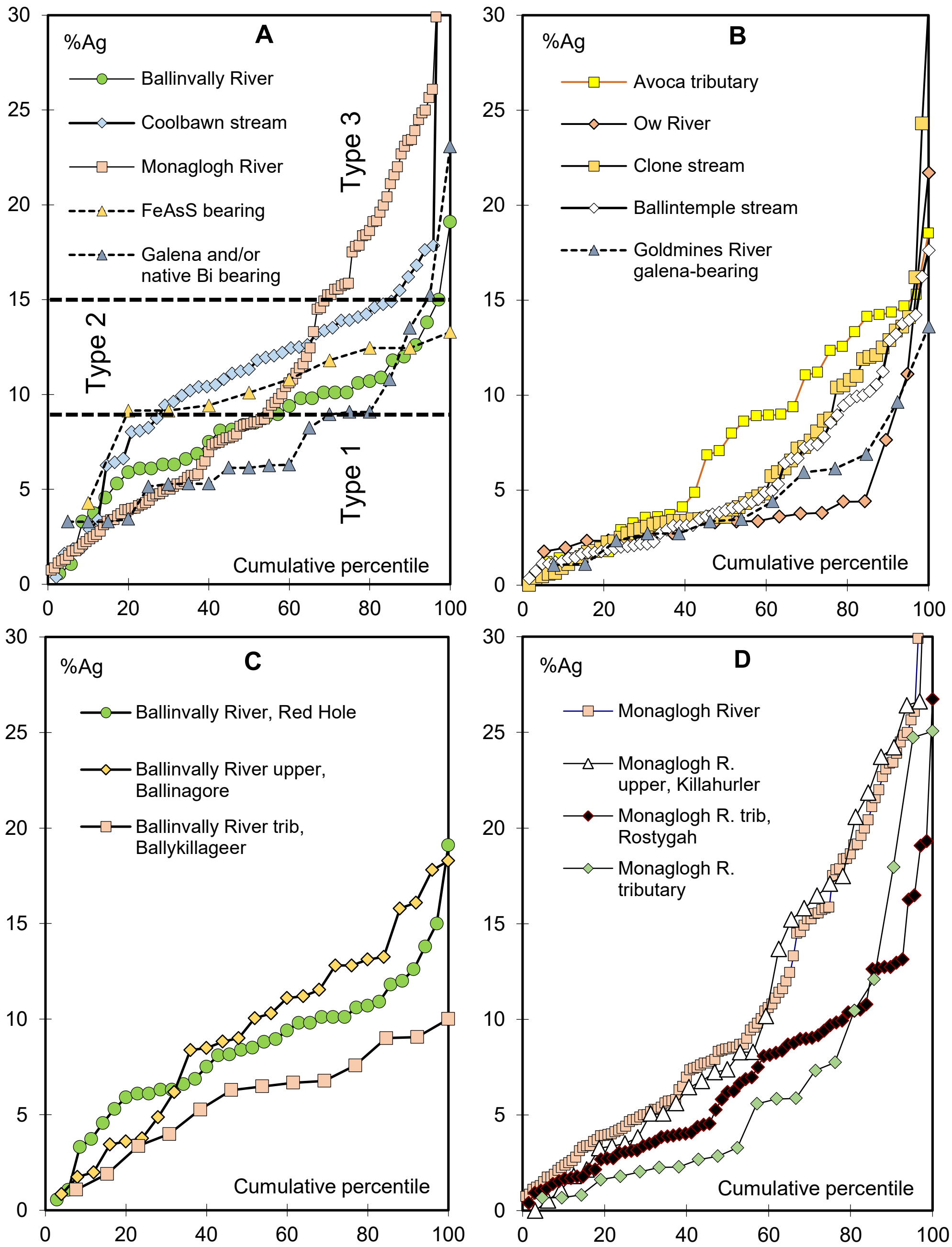

A
%Ag
Ballinvally River
Coolbawn stream
Monaglogh River
FeAsS bearing
Galena and/or native Bi bearing
Type 3
Type 2
Type 1
Cumulative percentile
B
%Ag
Avoca tributary
Ow River
Clone stream
Ballintemple stream
Goldmines River galena-bearing
Cumulative percentile
C
%Ag
Ballinvally River, Red Hole
Ballinvally River upper, Ballinagore
Ballinvally River trib, Ballykillageer
Cumulative percentile
D
%Ag
Monaglogh River
Monaglogh R. upper, Killahurler
Monaglogh R. trib, Rostygah
Monaglogh R. tributary
Cumulative percentile
0
5
10
15
20
25
30
0
20
40
60
80
100

Fig. 10 A—C

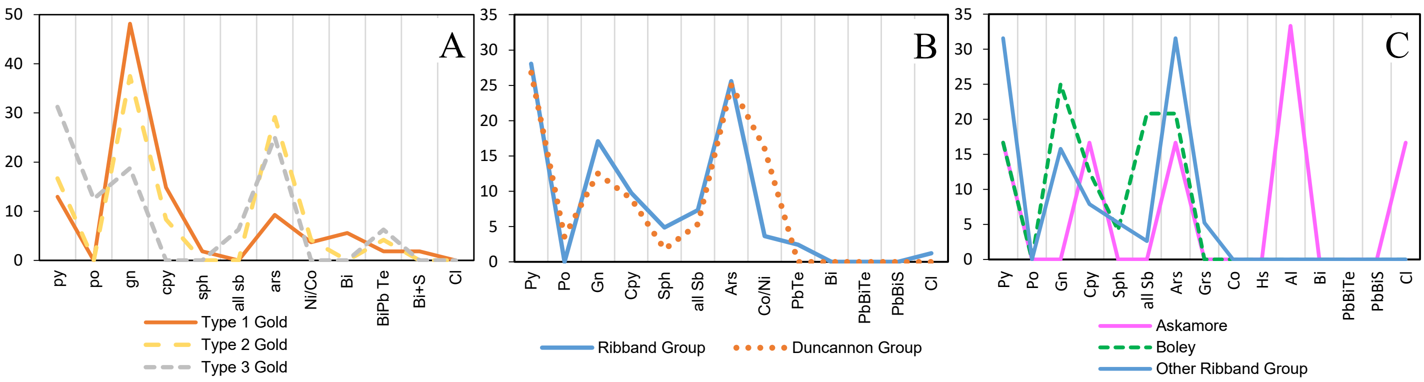
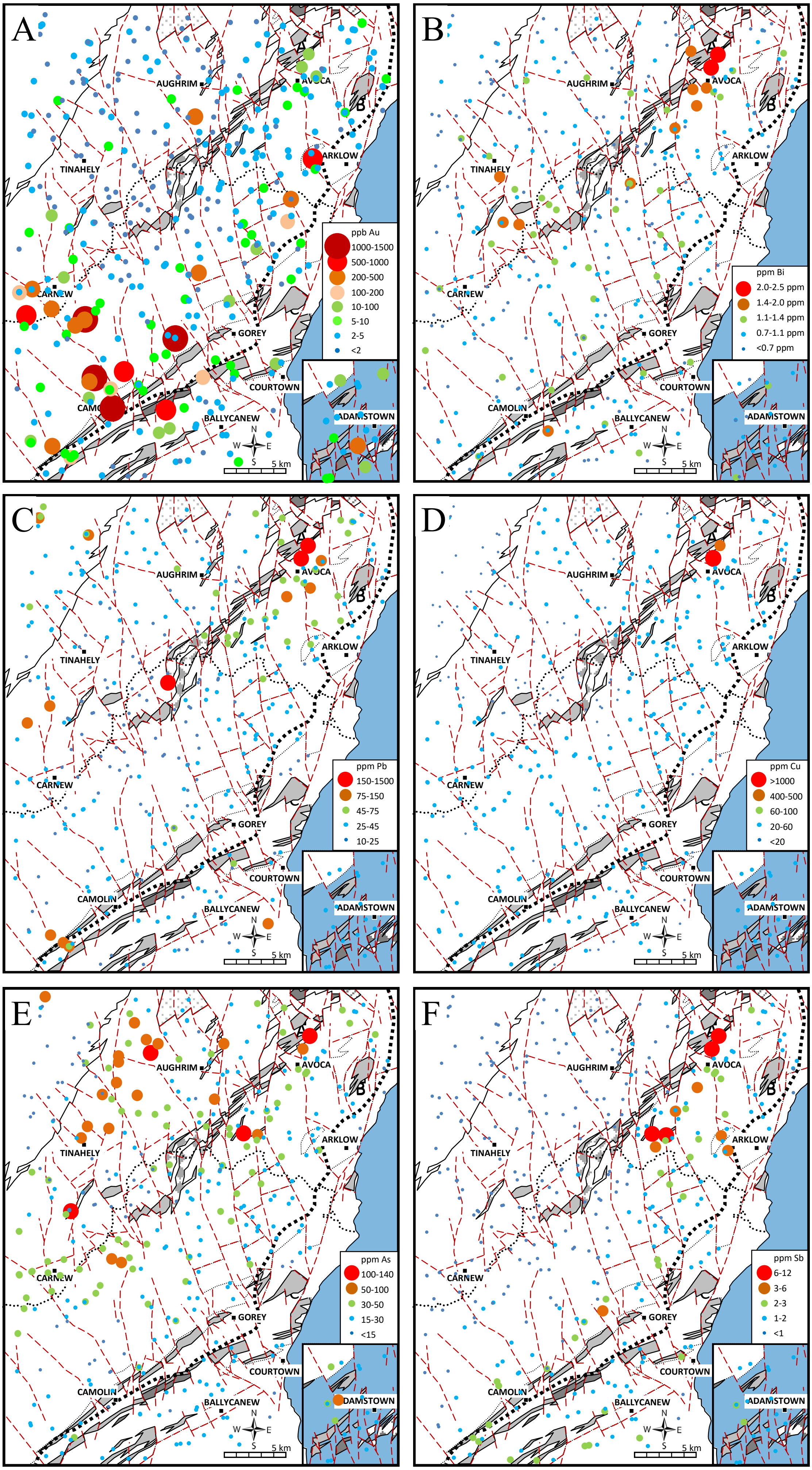

A
py
po
gn
cpy
sph
all sb
ars
Ni/Co
Bi
BiPb Te
Bi+S
Cl
Type 1 Gold
Type 2 Gold
Type 3 Gold
B
Py
Po
Gn
Cpy
Sph
all Sb
Ars
Co/Ni
PbTe
Bi
PbBiTe
PbBiS
Cl
Ribband Group
Duncannon Group
C
Py
Po
Gn
Cpy
Sph
all Sb
Ars
Grs
Co
Hs
Al
Bi
PbBiTe
PbBiS
Cl
Askamore
Boley
Other Ribband Group

Fig. 11 A—F



A
AUGHRIM
AVOCA
ARKLOW
TINAHELY
CARNEW
GOREY
COURTOWN
BALLYCANEW
ADAMSTOWN
ppb Au
1000-1500
500-1000
200-500
100-200
10-100
5-10
2-5
<2
5 km
B
ppm Bi
2.0-2.5 ppm
1.4-2.0 ppm
1.1-1.4 ppm
0.7-1.1 ppm
<0.7 ppm
CAMOLIN
C
ppm Pb
150-1500
75-150
45-75
25-45
10-25
D
ppm Cu
>1000
400-500
60-100
20-60
<20
E
ppm As
100-140
50-100
30-50
15-30
<15
F
ppm Sb
6-12
3-6
2-3
1-2
<1

Fig. 11 G—J

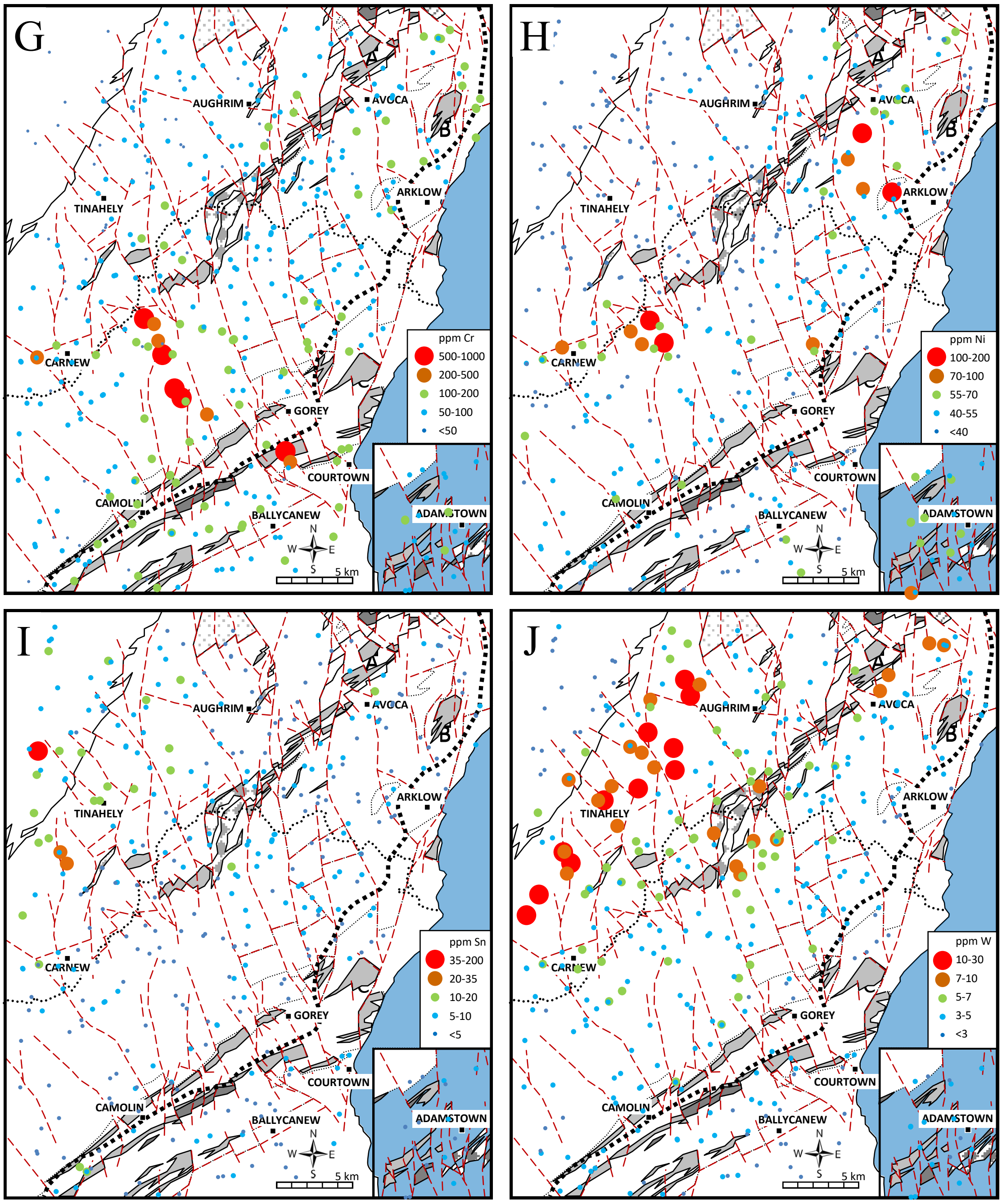
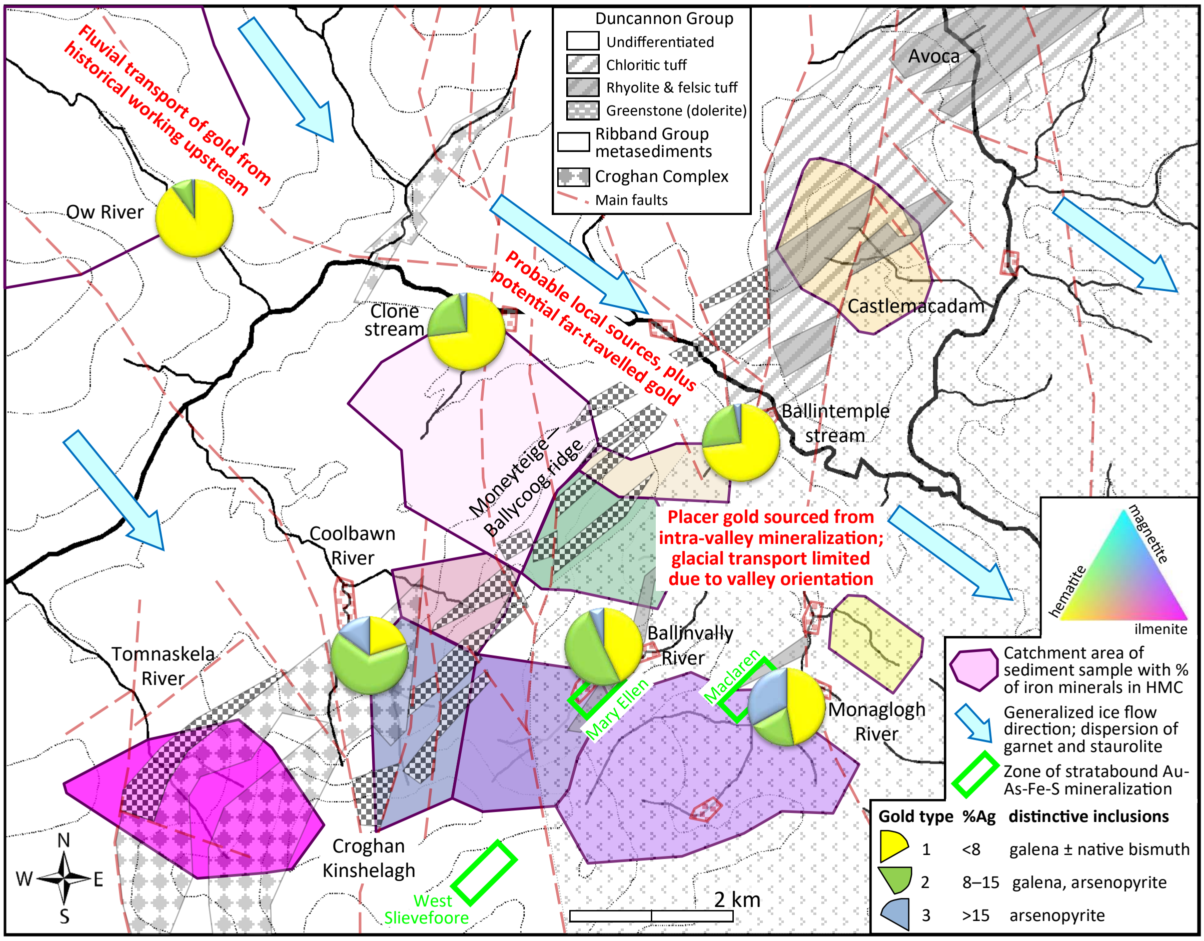

G
AUGHRIM
AVOCA
ARKLOW
TINAHELY
CARNEW
GOREY
COURTOWN
CAMOLIN
BALLYCANEW
ADAMSTOWN
ppm Cr
500-1000
200-500
100-200
50-100
<50
N
W
E
S
5 km
H
AUGHRIM
AVOCA
ARKLOW
TINAHELY
CARNEW
GOREY
COURTOWN
CAMOLIN
BALLYCANEW
ADAMSTOWN
ppm Ni
100-200
70-100
55-70
40-55
<40
N
W
E
S
5 km
I
AUGHRIM
AVOCA
ARKLOW
TINAHELY
CARNEW
GOREY
COURTOWN
CAMOLIN
BALLYCANEW
ADAMSTOWN
ppm Sn
35-200
20-35
10-20
5-10
<5
N
W
E
S
5 km
J
AUGHRIM
AVOCA
ARKLOW
TINAHELY
CARNEW
GOREY
COURTOWN
CAMOLIN
BALLYCANEW
ADAMSTOWN
ppm W
10-30
7-10
5-7
3-5
<3
N
W
E
S
5 km

Fig. 12


Duncannon Group
Undifferentiated
Chloritic tuff
Rhyolite & felsic tuff
Greenstone (dolerite)
Ribband Group metasediments
Croghan Complex
Main faults
Fluvial transport of gold from historical working upstream
Probable local sources, plus potential far-travelled gold
Placer gold sourced from intra-valley mineralization; glacial transport limited due to valley orientation
Avoca
Castlemacadam
Ow River
Clone stream
Ballintemple stream
Moneyteige–Ballycoog ridge
Coolbawn River
Tomnaskela River
Ballinvally River
Monaglogh River
Croghan Kinshelagh
Mary Ellen
Maclaren
West Slievefoore
2 km
N
W
E
S
magnetite
hematite
ilmenite
Catchment area of sediment sample with % of iron minerals in HMC
Generalized ice flow direction; dispersion of garnet and staurolite
Zone of stratabound Au-As-Fe-S mineralization
Gold type %Ag distinctive inclusions
1 <8 galena ± native bismuth
2 8–15 galena, arsenopyrite
3 >15 arsenopyrite

Moles & Chapman - SE Ireland placer gold - Table 2

Map code	Site / river name	County	Irish Grid ref.	Abundance	Number of grains	Median %Ag	Median %Ag category	No. grains with inc.	% with inc.	Total no. inclusions	Metalliferous inclusion species: Py	Po	Gn	Cpy	Sph	CuSbS	Ars	Grs	Alt	Bi	Others
1	Kilmacoo north	Wicklow	T 211 850	very low	2	-	-	0	0	0											
2	Knockanode	Wicklow	T 193 823	very low	4	3.7	low	1	25	2			1								Native As
3	Avoca tributary	Wicklow	T 214 819	low	33	8.0	high	6	18	7	1		1	1		1	3				
4	Ow River	Wicklow	T 111 800	low	19	3.4	low	6	32	8	1	1	4	2							
5	Castlemacadam	Wicklow	T 194 792	very low	4	3.4	low	0	0	0											
6	Clone stream	Wicklow	T 140 785	high*	62	3.6	low	5	8	6			9	2	1						
6	Clone stream	Wicklow	T 140 785	high*	51	4.0	low	5	10	6											
7	Ballintemple stream	Wicklow	T 177 780	high*	62	3.9	low	9	15	11	3		1	1			3		2		Wittichenite
8	Tomnaskela River	Wicklow	T 105 738	very low	2	-	-	0	0	0											
9	Coolbawn River	Wicklow	T 132 750	high*	46	11.5	high	3	7	3			3								
10	Ballinvally River trib., Ballykillageer	Wicklow	T 165 761	low	13	6.5	medium	1	8	1			1								
11	Ballinvally River, Red Hole	Wicklow	T 160 745	high*	81	8.5	high	16	19	22	5		5	1			5	1		2	Plumbogummite x3
12	Ballinvally River upper, Ballinagore	Wicklow	T 152 742	low	25	9.5	high	3	8	3	1			1							Tsumoite
13	Monaglogh R trib., Rostygah	Wicklow	T 182 754	high*	68	6.2	medium	15	22	17	3		9	1			2	1			Unidentified CuAsS
14	Monaglogh River	Wicklow	T 180 745	high*	60	8.4	high	6	10	8	4	1	7	1		1	4	1		1	
14	Monaglogh R duplicates 2 & 3	Wicklow	T 178 747	high*	73	8.3	high	9	12	12											
15	Monaglogh tributary	Wicklow	T 180 750	low	21	3.3	low	3	14	3							2	1			
16	Monaglogh R upper, Killahurler	Wicklow	T 174 737	very low	5	7.2	medium	0	0	0											
A	Kilcloran	Wexford	T 054 533	low	46	6.2	medium	3	7	3	2		1								
B	Hyde Park	Wexford	T 208 665	medium	81	5.7	medium	9	11	11	2		4			4	1				
C	Cullenoge	Wexford	T 207 647	low	50	5.0	low	5	10	12	4		2	3			2	1			
D	Coolnacon Bridge	Wexford	S 839 307	medium	91	3.2	low	8	9	8	2		1	3	1		1				
E	Misterin	Wexford	S 842 264	very low	13	3.8	low	1	8	1								1			
F	Ballyshannon	Wexford	S 850 255	low	48	4.4	low	2	4	3	1							2			
G	Boley Lower	Wexford	T 069 562	high	192	5.9	medium	17	9	24	4		6	3	1	5	5				
H	Rossminoge South	Wexford	T 069 576	very low	20	5.0	low	0	0	0											
I	Ballykale	Wexford	T 160 563	high	167	7.5	medium	13	8	19	4	1	3	3			7	1			
J	Newbridge Wood	Wexford	T 060 558	low	21	4.8	low	1	5	1							1				
K	Askamore Burn	Wexford	T 025 585	low	30	6.5	medium	4	13	4	1			1			1		2		Clausthalite
K	Askamore duplicate	Wexford	T 024 583	low	30	5.8	medium	2	7	2											
L	Milshoge	Wexford	T 065 520	high	96	7.3	medium	3	3	4	1			1			2				
M	Knockrobin Lower	Wexford	T 082 516	low	18	5.2	low	1	6	1							1				
N	Ballyeden	Wexford	T 099 517	low	68	6.3	medium	6	9	5	2	1					2				
Q	Huntingtown	Wexford	T 110 574	low	41	8.3	high	5	8	5	3					1	1				
R	Ballygarrett (Ballyowen)	Wexford	T 105 596	high	64	7.9	high	2	3	2	3		1		1	1	2				
R	Ballygarrett duplicate^	Wexford	T 115 607	high	114	7.5	medium	6	5	6											
S	Gibbett Hill	Wexford	S 961 576	medium	55	5.9	medium	3	5	3	1		1				1				
T1	Tombreen 1	straddle	T 003 622	low	30	7.4	medium	2	7	2			2	1			2	1			
T2	Tombreen 2	straddle	S 987 619	low	28	5.3	low	3	11	4											
V	River Bann, Holyfort	Wexford	T 122 641	very low	3	3.9	-	0	0	0											
W	S. Corbetstown^	Wexford	T 067 487	high	93	6.6	medium	3	3	3	3										
X	Coolnaveagh^	Wexford	T 146 573	medium	57	6.4	medium	4	7	5	1					1	1	1			Cobaltite
Y	Kilmichael^	Wexford	T 114 625	medium	30	7.0	medium	2	7	2	1			1							
Z	Ballyduff^	Wexford	T 115 502	medium	43	7.1	medium	5	12	8	1				1	1	3	1			Boulangerite
				Total:	2160			198		**247**	54	4	62	26	5	15	52	12	4	3	10

Site code	Site / river name	Barite	Hematite	Magnetite	Ilmenite	Rutile	Chrome spinel	Cassiterite	Ferberite	Tantalite	Monazite	Zircon	Garnet	Staurolite
1	Kilmacoo north	-	13	-	-	-	-	-	-	-	-	-	75	12
2	Knockanode	-	8	-	-	-	-	-	-	-	-	-	80	12
3	Avoca tributary	-	-	-	-	-	-	-	-	-	-	-	86	14
4	Ow River	-	-	-	-	-	-	-	-	-	-	-	85	15
5	Castlemacadam	-	27	-	10	-	-	-	-	-	-	-	42	21
6	Clone stream	-	-	-	5	-	2	5	2	-	-	-	68	18
7	Ballintemple stream	-	11	2	5	-	2	9	-	-	-	-	56	15
8	Tomnaskela River	-	-	-	75	-	3	6	2	-	-	2	12	-
9	Coolbawn River	-	20	37	30	-	-	-	5	-	-	-	8	-
9n	Moneyteige North	-	18	11	25	-	3	9	3	-	2	-	22	7
11	Ballinvally River, Red Hole	-	16	32	42	-	-	-	-	-	-	-	10	-
13	Monaglogh R trib., Rostygah	-	40	4	2	-	-	4	2	-	-	-	33	15
14	Monaglogh River	-	4	19	40	10	-	3	-	-	-	-	19	5
A	Kilcloran	-	11	-	50	-	-	2	2	-	16	3	16	-
B	Hyde Park	-	12	-	38	-	-	4	2	-	3	-	41	-
C	Cullenoge	-	15	-	55	-	-	-	-	-	-	8	22	-
D	Coolnacon Bridge	-	-	5	60	4	-	5	-	-	-	-	17	9
E	Misterin	-	-	5	68	6	-	2	-	-	-	-	13	6
F	BallyShannon	-	-	-	57	4	-	7	-	1	2	-	17	12
G	Boley Lower	-	9	-	7	-	3	17	19	2	29	-	14	-
H	Rossminogue south	-	-	-	39	-	10	5	-	-	20	2	24	-
I	Ballykale	-	8	-	39	-	12	4	2	1	-	2	32	-
J	Newbridge Wood	-	-	-	66	-	-	4	-	-	16	-	14	-
K	Askamore	-	-	-	5	-	-	54	10	4	3	-	24	-
L	Milshoge	-	9	-	54	9	-	12	-	-	10	-	6	-
M	Knockrobin Lower	-	7	-	60	6	-	-	-	-	-	-	27	-
N	Ballyeden	-	11	-	45	3	-	3	-	-	-	4	34	-
P	Bolinready	-	9	-	39	-	-	-	-	-	-	-	52	-
Q	Huntingstown	-	3	-	67	-	6	3	-	-	-	3	18	-
R	Ballygarrett / Ballyowen	13	6	-	21	-	21	9	3	-	18	-	9	-