Reconnaissance-scale prospectivity analysis for gold mineralisation in the Southern Uplands-Down-Longford Terrane, Northern Ireland

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ABSTRACT

The Southern Uplands-Down-Longford Terrane in south-east Northern Ireland is prospective for Caledonian-age, turbidite-hosted orogenic gold mineralisation with important deposits at Clontibret in the Republic of Ireland and in Scotland. Geochemical and geophysical data from the DETI-funded Tellus project have been used, in conjunction with other spatial geoscience datasets, to map the distribution of prospectivity for this style of mineralisation over this terrane. A knowledge-based fuzzy logic modelling methodology using Arc Spatial Data modeller was utilised. The prospectivity analysis has identified several areas prospective for turbidite-hosted gold mineralisation, comparable to that at Clontibret and gold occurrences in the Southern Uplands of Scotland. A number of these either coincide with known bedrock gold occurrences or with areas considered prospective and targeted by previous exploration work, validating the predictive capability of the exploration model devised and its translation into a GIS-based prospectivity model. The results of the modelling suggest that as in other parts of the Southern Uplands the coincidence of regional strike-parallel structures and intersecting transverse faults are highly prospective, as these are likely to create zones of anomalous stress for fluid flow and deposit formation. Those areas in which there are no known gold occurrences are considered to be favourable targets for further exploration and should be followed up.

KEY WORDS: fuzzy logic; GIS; Southern Uplands; orogenic gold; mineral exploration

INTRODUCTION

It has long been recognised that integration of multiple geoscience datasets is advantageous for mineral exploration targeting. Geographical Information Systems (GIS) are now routinely used for the management, manipulation, processing and integration of voluminous spatial exploration datasets. Examination of multiple datasets in the GIS environment can aid the determination of features critical or incidental to the mineralisation process and emphasise patterns and associations that may not be obvious when the datasets are viewed in isolation. Prospectivity analysis is a GIS-based predictive spatial analysis technique used to integrate multiple exploration datasets in the framework of a mineral deposit model (Porwal and Kreuzer 2010). The output of the process is a map displaying favorability for the occurrence of a particular mineral deposit type.

This study integrates numerous datasets including high-resolution airborne geophysical and geochemical data, from the Tellus Survey (2004–2007) to delineate favourable areas for Caledonian-age, turbidite-hosted orogenic gold mineralisation in south-east Northern Ireland. The study area (3725 km^2) covers part of a major tract of Lower Palaeozoic marine sedimentary rocks which hosts gold mineralisation in the Republic of Ireland and Scotland with minor occurrences known in Northern Ireland (Figure 1).

Insufficient known mineral occurrences or 'training sites' precluded the use of data-driven or empirical modelling techniques in which the weights assigned to evidential themes are derived statistically by analysing the relationship between known mineral occurrences and geological features. Instead a knowledge-driven or conceptual approach was used in which model parameters are dictated by 'expert' opinion (Bonham-Carter 1994; Porwal and Kreuzer 2010).

In knowledge-driven analysis the geoscientist identifies those criteria in the mineral deposit model that are critical to the formation of a deposit. The formation of a mineral deposit is likely to depend on the spatial and temporal coincidence of multiple controlling processes. These cannot be directly mapped, although we can identify proxies of these processes e.g. faults active at the time of mineralisation represent potential pathways for mineralising fluids (Porwal and Kreuzer 2010). It is necessary to determine which of these processes or features can be identified in the exploration data to develop an exploration model. Frequently only part of the mineral deposit model can be mapped with the data available and the exploration model defines which evidential data layers are likely to be good predictors for the mineral deposit being targeted and their appropriate weighting or significance in the model.

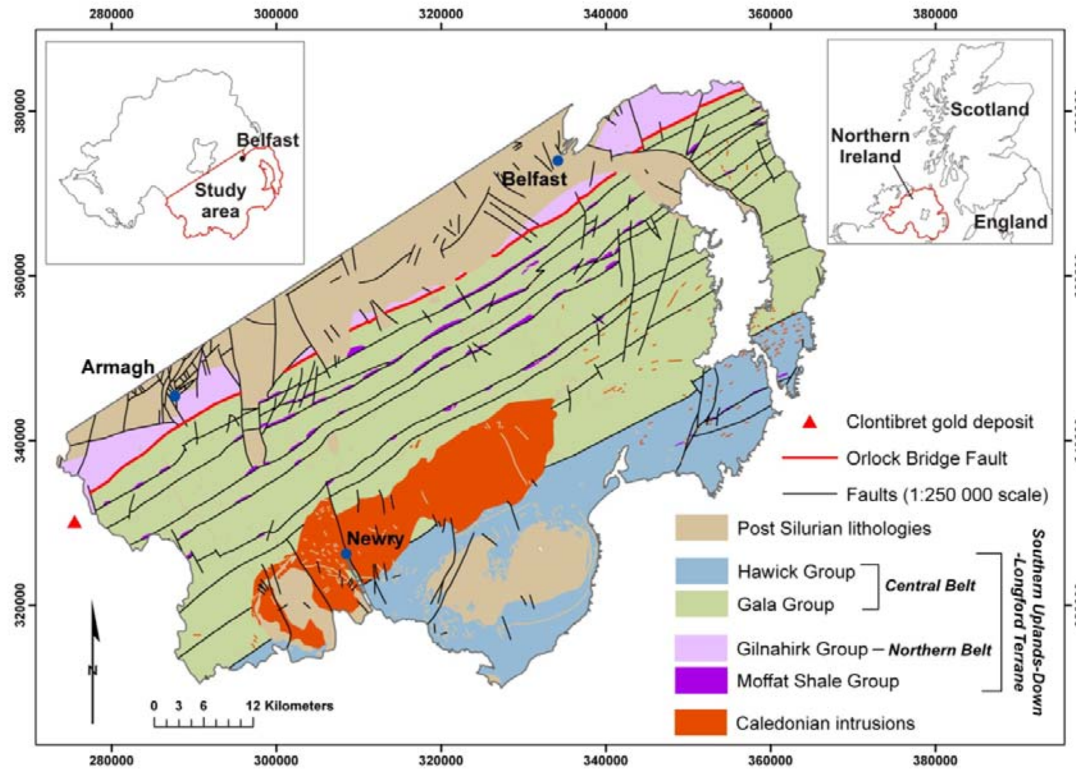

Figure 1. Location of the study area and the geology of the Southern Uplands-Down-Longford Terrane © Crown copyright and database right (2012) DMOU205.

The application of spatial modelling to mineral exploration targeting is a rapidly evolving research area and knowledge-driven analysis has been applied to exploration for gold deposits in a number of areas including the Yilgarn Block of Western Australia (Groves et al. 2000; Knox-Robinson 2000), the Lynn Lake Greenstone Belt of Canada (Rogge et al. 2006), the northern Fennoscandian Shield of Finland (Nykänen and Ojala 2007) and the Philippines (Carranza and Hale 2001). In the UK prospectivity analysis has been employed to determine favorable areas for gold mineralisation in Neoproterozoic rocks in Scotland (Gunn et al. 1997), turbidite-hosted gold deposits in the Lower Paleozoic Welsh Basin (Cooper et al. 2000) and epithermal gold mineralisation in the Devonian rocks of northern Britain (Gunn and Rollin 2000).

FUZZY LOGIC METHOD

A detailed account of fuzzy set theory is provided by a number of authors (e.g. An et al. 1991; Bonham-Carter 1994; Knox-Robinson 2000) and only a brief summary is provided here. In classical set theory membership of a set is defined as either true (=1) or false (=0), there is no intermediate state. Given the complex interplay of multiple controls and considerable uncertainty surrounding the formation of mineral deposits this conventional approach is not always appropriate. In contrast the fuzzy logic method, based on fuzzy-set theory devised by Zadeh (1965), can be used to take into account the relative importance of various controls and subtleties which may have a bearing on mineral deposit formation. This approach allows assignment of weightings to exploration criteria on a continuous scale from 1 (full membership) to 0 (full non-membership). For example the presence of anomalous arsenic values in stream-sediment data is a favorable indicator gold mineralisation in our study area. If As values are split across a range of class intervals these can be attributed with different significance levels i.e. fuzzy membership values in the model. In this way original data sets are converted to layers consisting of fuzzy membership values. Following assignment of fuzzy membership values to evidential data layers they can be combined using fuzzy operators. Five fuzzy operators are routinely used for the integration of mineral exploration-related datasets and these are described in detail by An et al. (1991), Bonham-Carter (1994) and Carranza and Hale (2001) (Table 1). This study utilised the maximum operator (fuzzy OR) and the fuzzy gamma operator. The data pre-processing, fuzzification and data integration were conducted in ArcGIS, using the Spatial Data Modeller extension software (Arc-SDM, version 9.2) (Sawatzky et al. 2008), described by Raines and Bonham-Carter (2006).

Fuzzy operator	**Expression**
Fuzzy AND	$\mu_{\text{combination}} = MIN(\mu_{\text{A}}, \mu_{\text{B}}, \mu_{\text{C}} \ldots)$
Fuzzy OR	$\mu_{\text{combination}} = MAX(\mu_{\text{A}}, \mu_{\text{B}}, \mu_{\text{C}} \ldots)$
Fuzzy algebraic product	$\mu_{\text{combination}} = \Pi^{n}_{i=1}\, \mu_i$
Fuzzy algebraic sum	$\mu_{\text{combination}} = 1 - \Pi^{n}_{i=1}\,(1-\mu_i)$
Fuzzy gamma	$\mu_{\text{combination}} = (\Pi^{n}_{i=1}\, \mu_i)^{1-y}\,(1-\Pi^{n}_{i=1}(1-\mu_i))^{\gamma}$

Table 1. Fuzzy logic operators as described by Bonham-Carter (1994)

Since coding of a fuzzy logic model relies on subjective judgment it is critical to have a comprehensive understanding of the key controls on the mineralisation being sought and their relative importance, restricted to those components of the model that can be treated as mappable variables in the GIS environment with the data available. This frequently requires a considerable amount of data pre-processing to filter and extract relevant features and make generalisations to raw data sets.

GEOLOGICAL SETTING

For its limited size (about 14 000 km^2), Northern Ireland hosts a remarkable variety of geology with rock representatives from the Mesoproterozoic through to the Palaeogene. This study focuses on the Southern Uplands-Down-Longford (SUDL) Terrane in south-east Northern Ireland. This terrane, which extends across Scotland and Northern Ireland, is dominated by Lower Palaeozoic marine sedimentary rocks, one of the largest continuous outcrops of Ordovician and Silurian rocks in the British Isles (Steed and Morris 1986). This terrane formed during the Caledonian Orogeny and is an allochthonous prism dominated by well-bedded Ordovician and Silurian turbidite sequences consisting of greywacke sandstone, siltstone and mudstone. The sequence contains several thin formations composed of chert, tuffs and lavas and black and grey mudstones. Throughout the terrane the stratigraphy dominantly strikes ENE–WSW with a consistently steep dip (Anderson 2004).

The SUDL Terrane has been sub-divided into three strike-parallel belts: the Northern, Central and Southern Belts. The Northern Belt consists of Ordovician rocks, the Central Belt is early Silurian, containing abundant, small, Ordovician mudstone inliers and the Southern Belt is of mid- and late Silurian age. Only the Northern and Central Belts occur in the study area. Numerous major strike-parallel faults, the visible expression of presumed imbricate thrusts, spaced at between 1 and 5 km dissect the terrane into a series of fault bounded tracts (Morris, Steed and Wilbur 1986; Anderson 2004). It is proposed that these faults developed either within a south-east propagating thrust belt related to an accretionary fore-arc sedimentary prism (Leggett et al. 1979) or within a thrust stack related to a back-arc basin (Stone et al. 1987).

Of the strike-parallel faults the one separating the Northern Belt from the Central Belt is the most significant. This fault, known as the Orlock Bridge Fault (OBF), is a major Caledonian, sinistral strike-slip fault the trace of which extends for 400 km across Scotland and Ireland and has been interpreted as a major regional structure, possibly a terrane boundary. It is associated with a variable width zone of deformation, extending for over 1 km at some localities (Anderson and Oliver 1986; Barnes et al. 1995). Anderson and Oliver (1986) suggest that the OBF is primarily distinguished from other tract-bounding faults in the Southern Uplands by clear evidence of ductile deformation at depth, its lack of associated imbrications, its significant refolding and overprinting of the regional cleavage, and its pronounced affect on the stratigraphy. However, Barnes et al. (1995) contest that the OBF is effectively similar to other tract-bounding faults, which originated as thrusts within the imbricate stack.

South of the OBF, quartz-rich turbidite formations of the Gala Group occur in a series of accretionary tracts. Further south the Cloghy Fault separates the Gala Group from turbidites of the Hawick Group, which are generally fine-grained and rich in carbonate. Numerous smaller faults, with variable orientation and displacement directions due to the accretionary deformation, are also evident in the SUDL Terrane (Anderson 2004).

Intrusive rocks are a prominent feature of the study area. By far the largest igneous body is the Newry Igneous Complex (NIC), consisting of late orogenic I-type granite rocks, intruded into Silurian greywackes and mudstone. The complex was intruded around 400 Ma, post-dating the closure of the Iapetus Ocean and continental collision and coincident with the start of sinistral transpression in the Iapetus suture zone. Coeval lamprophyre dykes and subconcordant intrusions occur throughout the Central Belt, but are particularly prominent in the eastern half of the study area (Cooper and Johnston 2004a; Murphy 1987).

Upper Palaeozoic to Mesozoic sedimentary rocks extend over the Lower Palaeozoic strata in the northern part of the study area, obscuring the rocks of the Northern Belt. Palaeogene intrusive and extrusive rocks also occur. Rocks of the Lower Basalt Formation of the Antrim Lava Group extend across the Northern Belt and onto the Gala Group rocks. Palaeogene intrusive rocks form two complexes in the study area: the Mourne Mountains and Slieve Gullion, intruding the deformed Silurian turbidite succession. Minor Palaeogene igneous intrusions occur throughout the study area (Cooper and Johnstone 2004b).

MINERAL DEPOSIT MODEL AND DEPOSITS CHARACTERISTICS

Orogenic vein-hosted gold mineralisation

Although the SUDL Terrane has potential for a wide range of mineral deposit styles, including gold mineralisation genetically associated with Caledonian and later intrusives, the specific focus of this project was to determine its potential for Caledonian-age gold-bearing veins associated with the Palaeozoic turbidite successions. Goldfarb and others (2001) identified gold deposits associated with the Caledonian Orogeny in the British Isles as examples of Palaeozoic orogenic gold mineralisation. Palaeozoic turbidite-dominated sequences, deformed during the Caledonian orogeny, host numerous small Early and Middle Devonian gold deposits and include those of the Dolgellau Gold Belt of North Wales (Shepherd and Bottrell 1993), those in eastern and western Ireland (McArdle 1989) and in the Western Highlands of Scotland (Curtis et al. 1993). Models and descriptions of Phanerozoic orogenic gold deposits globally and in the British Caledonides were studied to determine the key characteristics of these deposits (Table 2).

Characteristic	Identified in project area
Collisional tectonic regime[1]	✓
Major accretionary boundary structures[1]	✓
'First-order' transcrustal structures[1]	✓
High angle 'second-order faults' related to major structures[2,3]	✓
Rocks of greenschist metamorphic grade[1]	✓
Mineralisation is post-peak metamorphism (i.e. late syncollisional)[2]	✓
Late syncollisional, intermediate to felsic magmatism[2]	✓
Ore mineralogy: gold, pyrite, arsenopyrite, native gold, Cu, Pb, Zn and Sb sulphides[1]	✓
Gangue mineralogy dominated by quartz ± carbonate	✓
Wall-rock alteration[1]	✓
Elevated values of Au, Ag, As, Sb, K, Li, Bi, W, Te, Cu, Pb, Zn, Cd in rock, soil and stream-sediment[2]	Selected elements (see text for discussion)
C-O-H ± N, near-neutral to low pH, low salinity fluids[1]	✓

Table 2. Characteristic features of Phanerozoic orogenic vein gold mineralisation and their occurrence in the study area (criteria compiled from: [1]Birerlein and Crowe (2000); [2]Ash and Alldrick (1996); [3]Nesbitt (1993)).

Gold mineralisation in the SUDL Terrane

A number of bedrock gold occurrences are described from the SUDL Terrane of Scotland and Ireland. The most significant is the Clontibret deposit, located in County Monaghan, Republic of Ireland. The Clontibret Sb-As-Au deposit is located in Ordovician andesitic greywackes about 1500 m to the north of the OBF. It consists of several NNW-trending 'lode zones' and an adjoining NE-trending stratabound 'stringer vein zone' (Steed and Morris 1986; Morris et al. 1986). Two main mineralising stages have been identified: arsenopyrite-pyrite within the 'lode zones' and disseminated in adjacent wall rock; and subsequent localised stibnite mineralisation (Morris et al. 1986). Further bedrock gold occurrences have been identified some 6 km along strike from Clontibret at Cargalisgorran and Tivnacree in Northern Ireland (Purcell et al. 2007). Geological relationships suggest that the Clontibret mineralisation is Caledonian age, consistent with a minimum K/Ar age of 360 Ma (Morris et al. 1986).

Stratigraphical controls

A spatial correlation exists between gold mineralisation and the Northern Belt of the SUDL Terrane. The OBF separates andesitic composition Ordovician greywackes of the Northern Belt from the more felsic Silurian greywackes of the Central Belt. The mineralisation at Clontibret is located entirely in mafic greywackes on the northern side of the OBF (Steed and Morris 1997). It is has been suggested that the Northern Belt greywackes may represent a source of metals or could be more chemically reactive favouring mineral deposition (Morris et al. 1986; Steed and Morris 1986). Stone et al. (1995) indicated a regional arsenic, lead and zinc enhancement in the northern part of the Scottish Southern Uplands relative to the southern part. It is suggested that arsenic and gold were preconcentrated in the back-arc sector of the Southern Uplands creating a 'sedimentary reservoir' for gold in the older greywacke formations. This concept is further supported by studies on gold mineralisation in Scotland, which indicated that mineralising fluids were derived at least partly from the greywacke country rocks, which were a significant source of reduced sulphur, arsenic and bismuth (Stone et al. 1995; Lowry et al. 1997). In summary the Northern Belt, which contains anomalous levels of metals and is proven to be a source of mineralising fluids is considered most prospective for gold deposit formation.

Although, based on the discussion above, the Northern Belt would appear to be most prospective for gold deposit formation, the Glendinning gold deposit is hosted in rocks of the Central Belt in Scotland, indicating that it is also prospective for gold mineralisation and that more mafic greywackes are not a prerequisite for gold deposit formation. Upper Palaeozoic, Mesozoic and Palaeogene rocks, which are younger than the Caledonian-age mineralisation, are not prospective (Table 3).

Geological grouping	**Rank**
Northern Belt	10
Central Belt	6
Caledonian intrusives	6
Post-Silurian lithologies	0

Table 3. Relative ranking of geological groupings based upon favourability for hosting gold mineralisation (10 = highest favourability).

Igneous rocks

On a global scale felsic to intermediate intrusions are common features in terranes hosting Phanerozoic orogenic gold mineralisation. However, the genetic relationship between intrusive rocks and gold mineralisation remains unclear with considerable differences between metalliferous provinces (Nesbitt 1993). In the Southern Uplands of Scotland many gold occurrences display a close spatial relationship with granitoid plutons either being hosted in intrusive bodies, at the contact with the country rock or in close proximity to an intrusive body. Naden and

Caulfield (1989) indicated that most hydrothermal alteration associated with gold mineralisation in the Southern Uplands occurred within 20 Ma of intrusive emplacement. At one gold occurrence in Scotland it is suggested that sulphide sulphur was derived from both the host intrusion and nearby strata. It is proposed that intrusion of granitoids may have generated hydrothermal systems at and within the margins of plutons, mobilising fluids from within the country rocks (Naden and Caulfield 1989). In contrast igneous rocks are very rare in the immediate vicinity of the Clontibret deposit and no volcanic units or major igneous plutons are exposed within 10 km of the mineralisation (Morris et al. 1986; Steed and Morris 1997). A few minor sills are recorded at Clontibret and a zone of hornfelsed greywacke occurring to the south of the deposit may indicate concealed intrusions at depth (Steed and Morris 1986; Steed and Morris 1997). It is notable that the Glendinning gold deposit in Scotland which displays many features in common with Clontibret is located entirely in greywackes, with no associated major intrusive bodies (Gallagher et al. 1983).

In summary, a spatial association with post-tectonic intrusives is evident at some gold occurrences in the SUDL Terrane but is not a universal feature and the genetic relationships remain unclear (Gunn and Plant 1998). Steed and Morris (1997) suggested the association between gold mineralisation and intrusions may solely reflect zones of structural anisotropy developed around intrusions, facilitating the development of brittle fracture systems.

Structural controls

Orogenic gold mineralisation is structurally controlled at a variety of scales (Bierlein and Crowe 2000). The most significant gold provinces in metamorphic belts are related to first-order, major crustal structures, which represent pathways for large volumes of ore-forming fluids (Goldfarb et al. 2005). As previously discussed, major strike-slip faults are a conspicuous feature of the SUDL Terrane and are considered to have controlled regional fluid flow. Of these the OBF represents the most pronounced structural break. Gold occurrences in the SUDL Terrane display a close spatial relationship to the OBF. Clontibret is located about 1500 m north of the OBF. A further indication of the importance of the OBF as a control on mineralisation in the SUDL Terrane is provided by clusters of base metal vein mineralisation located on or adjacent to the structure. Orogenic gold deposits are almost always hosted in second-order faults, which represent zones of high fluid flux and act as structural traps for ore deposition (Bierlein and Crowe 2000). The main vein system at Clontibret consists of a series of discordant NNW-trending ‘lode zones’, hosted in a late-stage, brittle fracture system, which post-dates the principal Caledonian deformation (Steed and Morris 1986). Cruise and Farrell (1993) conclude that the mineralisation at Clontibret is directly associated with faulting and that structural intersections represent the most promising targets in the district. As an indication of the potential for mineralisation associated with other strike-slip faults in the terrane, gold mineralisation occurs to the south of Clontibret in a subordinate shear zone parallel to the OBF (Steed and Morris 1997).

Mineralogy and geochemical signature

Deposit mineralogy has a direct bearing on identifying the correct geochemical criteria to use in mineral exploration. Throughout the SUDL Terrane gold occurs in association with arsenopyrite and pyrite, while at some deposits stibnite is also present (Steed and Morris 1997).

Gold occurrences in the SUDL Terrane frequently display two stages of mineralisation: (i) an early arsenopyrite-pyrite-gold bearing phase followed by; (ii) sulphides of base-metals, antimony and arsenic. At Clontibret two main stages of mineralisation are evident: (i) fine-grained auriferous arsenopyrite-pyrite within the ‘lode zones’ and disseminated in adjacent wall rocks; and (ii) subsequent more localised stibnite mineralisation. Both episodes of mineralisation are cross-cut by minor carbonate ± sphalerite ± chalcopyrite ± galena veinlets (Morris et al. 1986). At Clontibret pyrite always occurs in association with arsenopyrite. Other minerals associated with the arsenopyrite-pyrite mineralisation are sphalerite, chalcopyrite, tetrahedrite (Cu-Sb) and a Ni-Co phase (Steed and Morris 1986).

Lithogeochemical studies on Clontibret samples indicate a consistent positive relationship between arsenic and gold values (Steed and Morris 1986). Arsenopyrite- and pyrite-bearing samples from Clontibret are enriched in gold, bismuth, and to a lesser extent nickel, cobalt, copper, zinc and possibly chromium relative to unmineralised material. Stibnite-bearing material is enriched in lead and zinc. These associations reflect the mineralogy of the deposit with minor bismuth present in arsenopyrite, cobalt and nickel in pyrite, and copper and zinc resulting from inclusions of chalcopyrite, tetrahedrite and sphalerite in pyrite (Morris et al. 1986). Gold is rarely associated with the stibnite mineralisation and antimony and gold values from the same samples show no correlation (Steed and Morris 1986; Morris et al. 1986). At the comparable Glendinning deposit in Scotland arsenic, antimony, mercury, copper, lead and zinc drainage anomalies extend up to 5 km north-east of the deposit (Gallagher et al. 1983).

Relationship to other mineral occurrences

The most common type of mineralisation in the SUDL Terrane is quartz-carbonate veins containing sphalerite and galena (Steed and Morris 1997). A spatial relationship exists between the base metal mineralisation and gold occurrences (Steed and Morris 1986). Quartz-galena-sphalerite veins with a similar orientation to the gold-bearing veins at Clontibret occur in the area surrounding the deposit, and are thought to be part of the same vein swarm (Steed and Morris 1997; Morris, et al. 1986). A potential association between base-metal mineralisation and gold deposits is further supported by the work of Baron and Parnell (2005). They identify two stages of mineralisation in many of the base metal occurrences in south-west Scotland and Northern Ireland, the first related to Caledonian metamorphism and the second of probable Carboniferous age. It concluded that the mineralised fractures were exploited by both Caledonian metamorphic fluids (potentially auriferous) and later Carboniferous base-metal bearing fluids (Baron and Parnell 2005). In addition it is possible that the later base-metal bearing fluids remobilised Caledonian gold, as has been demonstrated in the Dalradian of Northern Ireland (Wilkinson et al. 1999).

EXPLORATION MODEL AND EVIDENCE LAYERS

Based on the general characteristics of Phanerozoic orogenic vein-gold mineralisation and the specific characteristics of gold mineralisation in the SUDL Terrane, with a particular focus on Clontibret, a range of exploration criteria was defined for use in the analysis. The data layers used to provide information relating to these criteria are summarised in Table 4.

Stratigraphical criteria

The geology of the study area was generalised and re-classified into four groupings so that different weighting levels could be allocated in the prospectivity model. The Northern Belt on account of its favourability for hosting gold mineralisation was allocated the greatest significance in the model. The Central Belt, although less favourable than the Northern Belt, is considered prospective because it is known to host gold mineralisation and numerous occurrences of non-auriferous vein style mineralisation. It is not possible to differentiate between the geological groups or individual tracts within the belts in terms of favourability for mineralisation, therefore these were processed as a single entity in the model.

	Exploration criteria	Rationale	Data source	Evidence layer
Stratigraphical criteria	Northern Belt (Gilnahirk and Strokestown groups)	Strong spatial correlation between gold mineralisation and mafic greywackes of the Northern Belt	1: 250 000 scale geological map	Generalised Northern Belt geology
	Central Belt (Moffat Shale, Gala and Hawick groups)	More felsic greywackes appear less prospective based upon known spatial distribution of gold occurrences, no inherent metal enrichment and a chemistry possibly less favourable for mineral deposition	1: 250 000 scale geological map	Generalised Central Belt geology
	Igneous rocks	Display close spatial relationship with gold mineralisation in Scotland, but not a universal feature of the terrane and largely absent in the vicinity of Clontibret	1: 250 000 scale geological map	Caledonian intrusive rocks
	Upper Palaeozoic, Mesozoic and Palaeogene rocks	Too young to host gold mineralisation of the age being targeted	1: 250 000 scale geological map	Generalised younger rocks
Structural criteria	Orlock Bridge Fault	A major sinistral shear zone and the most pronounced structural break in the study area, which displays a close spatial relationship to gold occurrences throughout the Terrane	1: 250 000 scale mapped faults	Buffered interpolated OBF
	Proximity to major strike-parallel faults	Control second-order structures and important fluid pathways, it is contested that these faults are effectively similar to the OBF	1: 250 000 scale mapped faults; Tellus Survey magnetic data	Buffered strike parallel faults
	Proximity to second-order structures	Structural control at a local level, ground preparation, enhanced permeability and particularly significant where they intersect regional structures	1: 250 000 scale mapped faults; Tellus Survey magnetic data	Buffered strike second-order structures
Geochemical criteria	Geochemical anomalies in soil and stream sediments for: Au-Ag-Bi-As-Cu-Pb-Zn-Co-Cr	Indicator of proximity to mineralisation. Pathfinders for gold based on geochemical characteristics of orogenic gold deposits, ore mineralogy and documented associations in the SUDL Terrane. Zn correlated significantly with Pb, Cu, and Co and therefore was not included as an evidence layer	Tellus Survey stream-sediment geochemistry (~1 sample/2.15 km^2) Tellus Survey soil geochemistry	Catchment restricted IDW grids for Au, As, Sb, Cu, Co, Pb (50 m grid, maximum search radius 2000 m) Parent material restricted grid for Au in soils

Mineral occurrences	Known mineralisation	Metalliferous mineralisation is the exploration target and well documented in the district. Although not necessarily auriferous, metallic mineralisation provides direct evidence of mineralising metalliferous fluids. Auriferous deposits typically have a mineralogy of pyrite, arsenopyrite, chalcopyrite, galena, sphalerite, stibnite	NI Mineral Occurrences Database Tellus Survey pan gold occurrences	Mineral localities (Au and industrial minerals removed) Buffered pan gold occurrences restricted to catchment

Table 4. Key exploration criteria for Caledonian-age, turbidite-hosted gold mineralisation vein gold mineralisation in the SUDL Terrane and associated evidence layers utilised.

Given the uncertain relationship between igneous rocks and gold mineralisation, and the scarcity of exposed igneous bodies in the vicinity of Clontibret, Caledonian intrusive rocks were allocated the same significance as the Central Belt rocks in the model. This ranking was based on the fact that intrusive rocks provide a suitable rheological medium for vein development, which is comparable with the surrounding sedimentary rocks and are known to host gold mineralisation in association with turbidites in Scotland. The weighting allocated to igneous rocks in the model did not attempt to reflect their potential as a heat source for driving hydrothermal systems or as a source of fluids and metals. These criteria are not easily translated into mappable evidence layers in the GIS and are therefore not considered in this model. The Upper Palaeozoic and younger rocks have no significance in the model as they are too young to be prospective for Caledonian-age gold mineralisation.

Structural criteria

Structural data was derived from two sources: published geological mapping and airborne geophysical data interpretation.

Mapping

As a result of its complex geological history a large number of structures occur in the study area. The OBF and other major strike-parallel faults were considered separately from other lineaments due to their perceived regional influence and their potential control on the location of mineralisation. On the 1:250 000 scale geological map the trace of the OBF is obscured in places by younger cover sequences. Accordingly the position of the structure in these areas was extrapolated to provide a continuous feature for inclusion in the modelling. Other major strike-parallel faults, defining tract boundaries on the 1:250 000 scale geological map, formed a separate dataset. These structures are potentially comparable to the OBF. The remaining faults shown on the 1:250 000 scale geological map were combined to create a separate dataset and allocated equivalent significance to the geophysical lineaments (Figure 2). It was not possible to discriminate structures based on age in the analysis as there is no attribution of faults by age for the 1:250 000 scale geological map. It is not appropriate to exclude structures which cross-cut Upper Palaeozoic and younger rocks as these are potentially reactivated Caledonian structures. In addition small variations in the regional stress field and local structural anisotropy means veins can potentially develop in structures of any orientation.

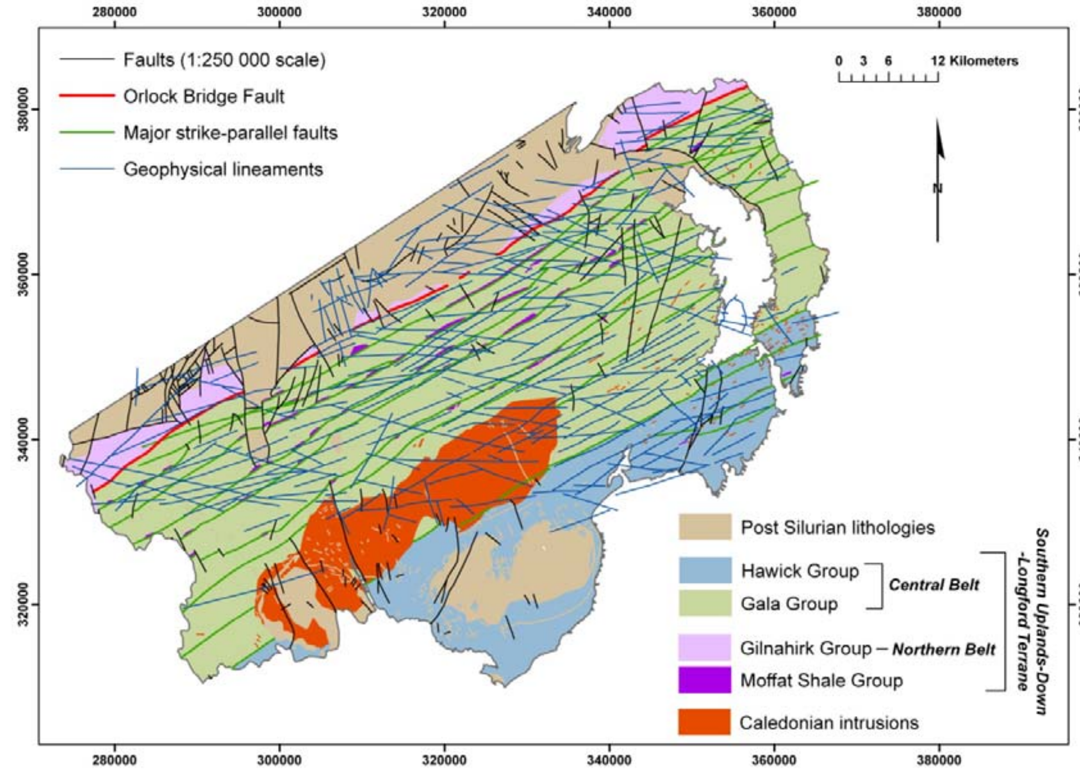

Figure 2. All the structural data incorporated into the prospectivity analysis © Crown copyright and database right (2012) DMOU205.

Geophysics

Aeromagnetic and electromagnetic data from the Tellus airborne survey were incorporated into the prospectivity analysis. The survey was flown at an elevation of 56 m in rural areas rising to 240 m in urban areas with survey lines spaced at 200 m intervals. Full details of the survey are documented in Beamish et al. (2007). Lineaments were extracted from various images of the geophysical data, chiefly the total magnetic intensity (TMI) (1st vertical derivative), TMI – (pseudo-gravity – 1st vertical derivative) and TMI (analytic signal). Emphasis was placed upon recognition of faults. Mapped faults, shear zones and geophysical lineaments were treated as a single evidence layer in the modelling and it is assumed that they represent the same style of deformation. Any lineaments coinciding with structures delineated on the 1:250 000 scale geological map were removed from the dataset to avoid double counting in the analysis.

Geochemical criteria

Stream sediment and soil geochemical data from the Tellus survey was incorporated in the prospectivity analysis. Standard BGS methodology was utilised throughout the field, laboratory and data processing stages of the geochemical survey (Johnson et al. 2005).

Stream-sediments

Stream-sediment samples comprising the < 150 µm fraction were gathered by wet sieving on site. Samples were collected from first- and second-order streams at an average density of 1 sample per 2.15 km^2 (Johnson et al. 2005). The stream-sediment samples were analysed for 58 elements by XRF and lead fire assay (for Au, Pt, Pd).

The use of the following pathfinder elements in this analysis was guided by the geochemistry of the target mineral deposit type: gold, arsenic, antimony, copper, cobalt and lead. Other elements displaying elevated values in mineralised material were excluded either as a result of showing strong correlations with the elements listed above (e.g. Zn correlated significantly with Pb, Cu, and Co), if the anomalous values could be attributed to other geological factors (e.g. Cr enrichment may be explained by abundant detrital Cr in the greywake host rocks) or if the element was representative of an exploration criterion evidenced by another theme (e.g. Ni could be utilised as indicative of regional variation in greywacke chemistry, which is accounted for by the geology evidential layer). The stream sediment data was log transformed, as a result of it being log-normally distributed (Table 5).

Gold, the principal target of the study, was given greatest significance in the modelling. Arsenic was allocated the greatest weighting after gold, owing to its close geochemical association with gold. The lower significance allocated to antimony reflects the observation at Clontibret that antimony and gold values are not correlated and that little gold is directly associated with the stibnite mineralisation. Copper and cobalt are allocated moderate significance in the model due to their enrichment in mineralised samples. Lead is allocated a lower significance than copper and cobalt as it is enriched in stibnite-bearing samples which are generally not auriferous.

	Au (ppb)	Log Au	As (ppm)	Log As	Sb (ppm)	Log Sb	Cu (ppm)	Log Cu	Pb (ppm)	Log Pb	Co (ppm)	Log Co
Mean	11	0.3	14.4	1	0.8	-0.2	39.7	1.6	45.7	1.6	25.2	1.4
Standard Error	2.3	0	0.5	0	0	0	0.5	0	1	0	0.4	0
Median	2	0.3	9.5	1	0.7	-0.2	36.8	1.6	34.6	1.5	22.8	1.4
Standard Deviation	88.5	0.5	19.9	0.3	0.6	0.3	20	0.2	38.3	0.3	13.4	0.2
Skewness	14.8	1.5	8.7	0.3	2.9	-0.1	2.8	-0.6	4.5	0.5	3.4	-0.6
Minimum	0.5	-0.3	0.5	-0.3	0.3	-0.6	4.1	0.6	1.3	0.1	1.5	0.2
Maximum	1844	3.3	356.7	2.6	7.4	0.9	260.4	2.4	556	2.7	202.2	2.3
Count	1440	1440	1440	1440	1440	1440	1412*	1412*	1352*	1352*	1440	1440

Table 5. Descriptive statistics for stream sediment data used in the prospectivity analysis; *indicates samples have been removed from the complete dataset of 1440 stream-sediment samples within 2 km of known mineralisation, within the same catchment.

Copper and lead values in stream sediments were excluded from the dataset if a known mineral occurrence in which the primary commodity was either copper or lead occurred within 2 km of the point, within the same catchment. Copper and lead were also processed using the fuzzy OR algorithm, to overcome the strong correlation they display. Although gold, arsenic and antimony all display strong correlations their evidence layers were not manipulated due to their greater importance as gold pathfinders.

The spatial variation of each of the six elements in stream sediments was interpolated using inverse distance weighting within catchments (50 m grid, maximum search radius of 2000 m) (Figure 3). Catchment areas were used to limit the inverse distance weighting and more realistically represent the area from which the stream sediments were derived (Figure 3 and 4). Data were selected at or above the 90^{th} percentile for gold in soils and gold, arsenic and antimony in stream sediments. The 75^{th} percentile was used for copper, cobalt and lead in stream sediments. These cut-offs were selected on the basis of data distributions. Threshold values defined using this method and used in the evidence layer for each element are shown in Table 6.

Soils

Soil samples were collected at 35–50 cm depth. The <2 mm fraction was analysed for 58 elements by XRF and lead fire assay (for Au, Pt, Pd). Relative to the stream-sediment data the gold in the soils evidential layer is given less significance in the modelling because in contrast to stream-sediment data it is essentially point source data reflecting local conditions only. Consequently it provides less evidence of gold mineralisation in the surrounding area. A method developed by Appleton et al. (2008) for potentially harmful element mapping was selected for interpolation of the soil gold data. This method takes into account variation both within and between geological units by calculating average gold values for each 1 km- bedrock-superficial geology combination (parent material, PM) using the five soil samples on the same PM located nearest to the centroid of each polygon. Percentiles were then used to classify the soil gold data (Figure 5 and Table 6 and 7).

Evidential theme	Theme weight	Class (for geochemistry - percentile range and ppb (Au) and ppm (other elements)	Class weight	Fuzzy membership value
Evidential maps of stream-sediment geochemistry				
Au	1.0	0–90 (<0.77815)	0.0	0.00
		90–95 (0.77816–1.04139)	0.8	0.80
		95–99 (1.04140–2.1757)	0.9	0.90
		99–100 (2.1758–3.2657)	1.0	1.00
As	0.9	0–90 (<1.4168)	0.0	0.00
		90–95 (1.4169–1.5640)	0.8	0.64
		95–99 (1.5641–1.8841)	0.9	0.72
		99–100 (1.8842–2.5523)	1.0	0.80
Sb	0.6	0–90 (<0.1761)	0.0	0.00
		90–95 (0.1762–0.2788)	0.8	0.48
		95–99 (0.2789–0.4714)	0.9	0.54
		99–100 (0.4715–0.8692)	1.0	0.60
Cu	0.5	0–75 (<1.6785)	0.0	0.00
		75–90 (1.6786–1.7860)	0.7	0.35
		90–95 (1.7861–1.8594)	0.8	0.40
		95–99 (1.8595–2.0141)	0.9	0.45
		99-100 (2.0142–2.4156)	1.0	0.50
Co	0.5	0–75 (<1.4698)	0.0	0.00
		75–90 (1.4698–1.5867)	0.7	0.35
		90–95 (1.5868–1.6840)	0.8	0.40
		95–99 (1.6841–1.8651)	0.9	0.45
		99-100 (1.8652–2.3058)	1.0	0.50
Pb	0.4	0–75 (<1.7302)	0.6	0.24
		75–90 (1.7303–1.9174)	0.7	0.28
		90–95 (1.9175–2.0468)	0.8	0.32

		95–99 (2.0469–2.3063)	0.9	0.36
		99–100 (2.3064–2.7451)	1.0	0.40
Evidential map of soil Au geochemistry	0.7	0–90 (<0.57449)	0.0	0.00
		90–95 (0.57450–0.75445)	0.8	0.56
		95–99 (0.75446–1.24230)	0.9	0.63
		99–100 (1.24231–2.16149)	1.0	0.70
Evidential map of stratigraphy	0.7	Northern Belt lithologies	0.9	0.63
		Central Belt lithologies	0.6	0.42
		Caledonian intrusives	0.6	0.42
		Post-Silurian lithologies	0.0	0.00
Evidential map of buffered distances from OBF	0.9	0–1.5 km	0.9	0.81
		1.5–2.0 km	0.8	0.72
		2.0–2.5 km	0.7	0.63
		2.5–3.0 km	0.5	0.45
		3.0–3.5 km	0.4	0.36
		3.5–4.0 km	0.3	0.27
Evidential map of buffered distances from major strike-parallel faults	0.8	0–1.0 km	0.9	0.72
		1.0–1.5 km	0.8	0.64
		1.5–2.0 km	0.7	0.56
		2.0–2.5 km	0.6	0.48
		2.5–3.0 km	0.4	0.32
Evidential map of buffered distances from second-order structures	0.8	0–0.5 km	0.9	0.72
		0.5–1.0 km	0.7	0.56

		1.0–1.5 km	0.3	0.24
Evidential map of buffered distances from mineral occurrences	0.5	0–0.5 km	0.8	0.40
		0.5–1.0 km	0.6	0.30
		1.0–1.5 km	0.4	0.20
		1.5–2.0 km	0.2	0.10
Evidential map of buffered distances from pan gold occurrence	0.8	0.0–1.0 km	0.9	0.72
		1.0–2.0 km	0.7	0.56
		2.0–3.0 km	0.4	0.32
		3.0–4.0 km	0.2	0.16

Table 6. Fuzzy membership values assigned to each evidential theme based on a combination of theme weight and class weight. Numbers in brackets following percentile ranges relate to log ppb ranges for gold and log ppm values for all other elements.

	Au (ppb)	**Log Au**
Mean	5.16	0.57
Standard Error	0.41	0.01
Median	3.03	0.48
Standard Deviation	9.44	0.27
Skewness	9.63	2.13
Minimum	2	0.3
Maximum	145.04	2.16
Count	539	539

Table 7. Descriptive statistics for gold soil data used in the prospectivity analysis.

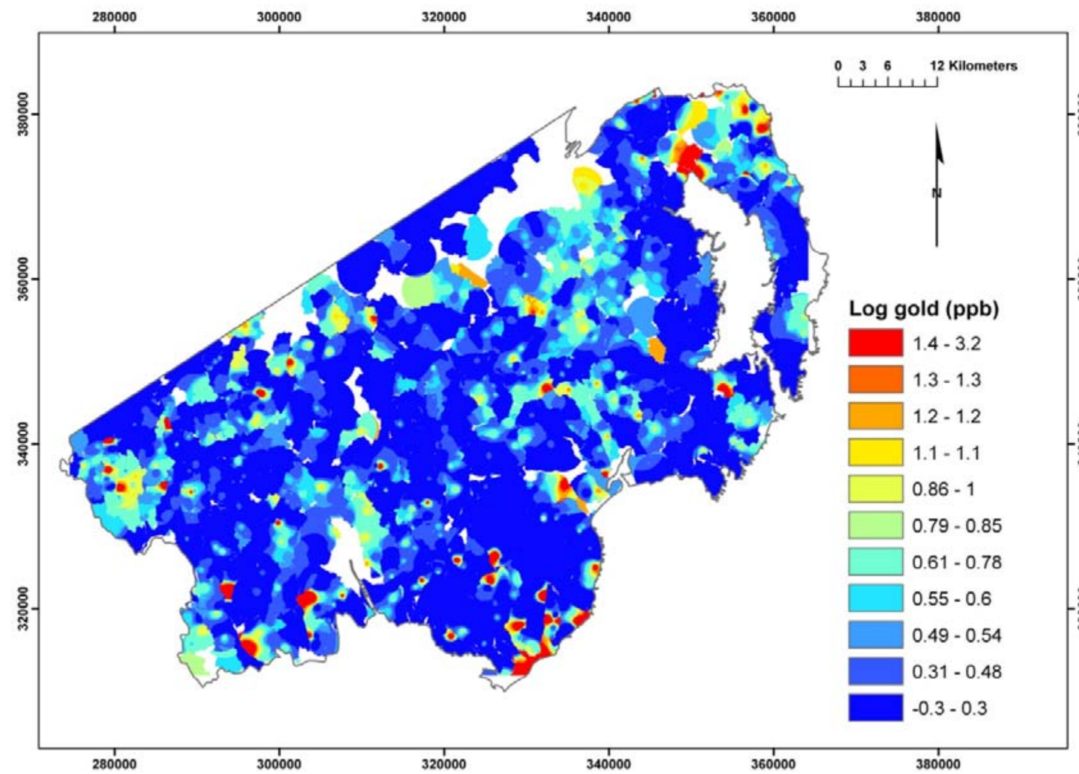

Figure 3. Log gold (ppb) in stream-sediment samples over the SUDL Terrane. Spatial variation interpolated by inverse distance weighting within catchments (50 m grid, maximum search radius of 2000 m) © Crown copyright and database right (2012) DMOU205.

Mineral occurrences

Mineral occurrences were incorporated into the prospectivity analysis (Figure 4). 156 minerals occurrences fall within the study area. Any occurrences unlikely to be related to auriferous mineralisation of the style being targeted were removed e.g. fluorite occurrences in Caledonian granites and occurrences with an obvious association with Palaeogene rocks. All the remaining mineral occurrences were associated with metallic minerals (*n=83)*. The rationale for inclusion of mineral occurrences in the analysis is that they provide direct evidence of mineralising processes. A relatively low weighting was assigned to this data in the prospectivity analysis to reflect the highly variable nature of the occurrences (i.e. in size and significance) and to ensure the analysis was not overly influenced by mineralisation which may not be auriferous (Table 6).

Observations of visible gold grains made during collection of panned heavy mineral concentrates in the Tellus geochemical sampling were utilised in the analysis (*n=19*) (Figure 4). Occurrences of gold in bedrock were excluded from the modelling as these were subsequently used to validate the results of the prospectivity analysis.

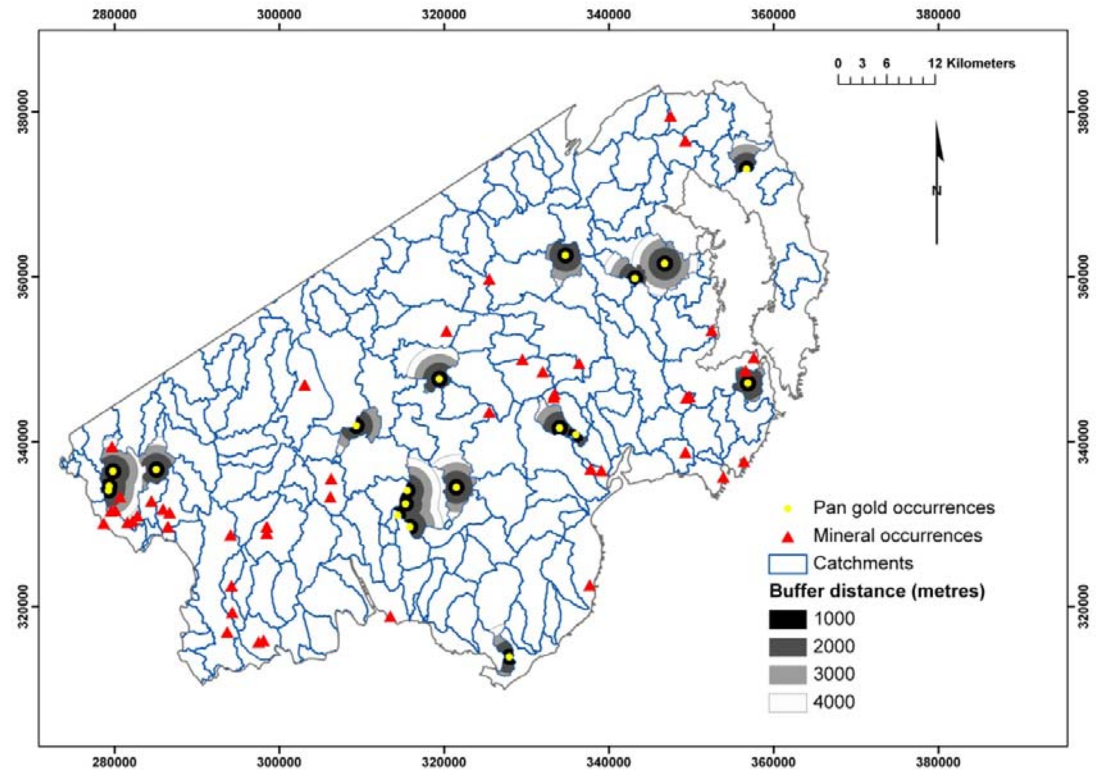

Figure 4. Drainage catchments defined for the study area showing buffered pan gold occurrences, with area of influence limited to the catchment of sampling. Mineral localities from the GSNI mineral occurrence database are also shown © Crown copyright and database right (2012) DMOU205.

Data processing

A proximity analysis ('buffering') was performed on linear features (faults, geophysical lineaments) and point themes (mineral occurrences) such that the weighting of a particular feature in the analysis decreases with increasing distance from that feature (Table 6). Features in each of the themes were buffered at variable intervals. The datasets were assigned variable buffer distances depending on the likely extent of influence of a particular feature. The extent of influence of visible gold grain occurrences was restricted to their catchment areas (Figure 4).

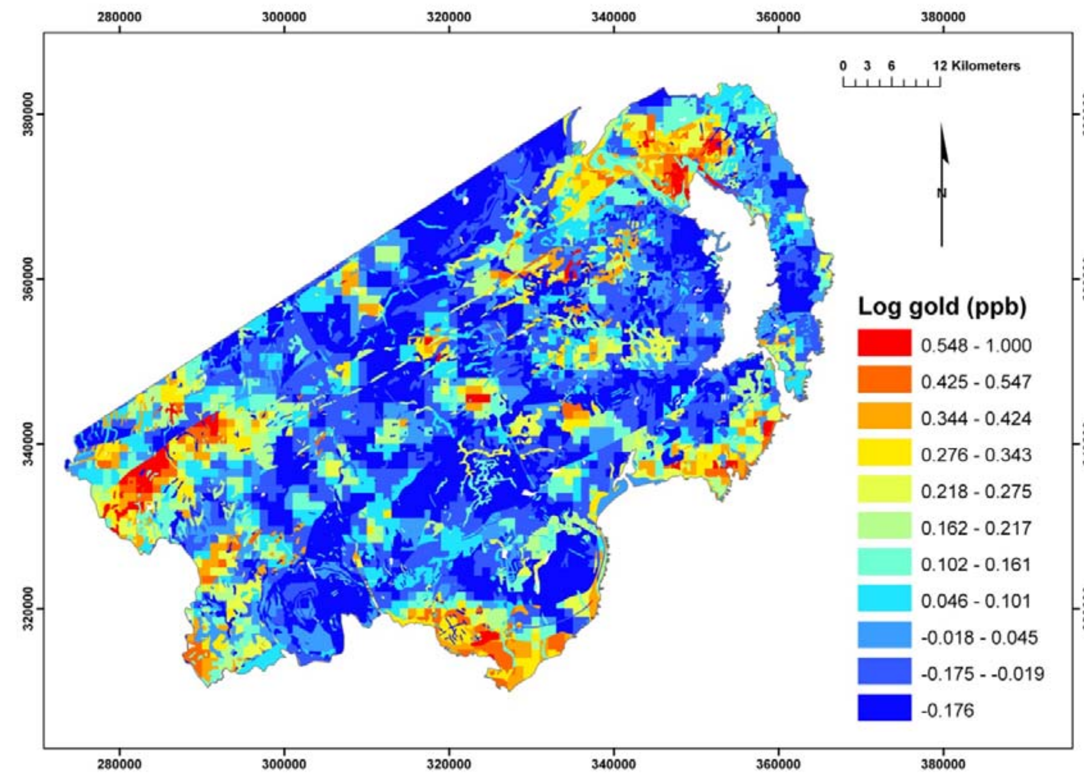

Figure 5. Log Au (ppb) averaged using the five nearest values on the same bedrock-superficial geology combination (PM). The interpolation was used as evidence layer. Method after Appleton, Rawlins and Thornton (2008) © Crown copyright and database right (2012) DMOU205.

FUZZIFICATION

Each evidential theme representative of exploration criteria (Table 4) for turbidite-hosted gold mineralisation in the SUDL Terrane of Northern Ireland was assigned a fuzzy membership value on the basis of the mineral deposit model discussed previously (Table 6). Bonham-Carter (1994) indicates that *fuzzy membership values must reflect the relative importance of each map, as well as the relative importance of each class of a single map.* Accordingly each evidential theme used in the model was allocated a significance value or map weight. Subsequently themes with multiple classes were internally ranked (Table 6). The combination of map weight and class weight provide the final fuzzy membership value. Areas without any favorable features, primarily due to lack of sufficient data, were assigned a no data value of 0.001.

The copper and zinc stream-sediment data were combined using the fuzzy OR operator to create an intermediate map. The fuzzy OR operator is used when two or more evidential themes represent the same evidence and the output membership values are controlled by the maximum values of any of the input maps (Bonham-Carter, 1994). All the evidence layers were then combined using the fuzzy gamma operator to produce the prospectivity map (Figure 6). The fuzzy gamma (γ) operator is a combination of fuzzy algebraic product and fuzzy algebraic sum. Its use is a compromise between the 'increasive' nature of fuzzy algebraic sum and the 'decreasive' effects of the fuzzy algebraic product (Table 1). γ values range between 0 and 1 and when γ is 0, the combination is the same as fuzzy algebraic product and, when γ is 1, it equals the fuzzy algebraic sum. The effect of selecting different γ values is examined by Bonham-Carter (1994). Previous studies suggest γ values in the region of 0.9 are most suitable for prospectivity mapping (An et al. 1991; D'Ercole et al. 2000; Mukhopadhyay et al. 2003; Tangestani and Moore 2003) although other studies have utilsed lower γ values of around 0.75 (Carranza and Hale 2001; Nykanen et al. 2008; Porwal et al. 2003). Choice of γ value is ultimately subjective and several were tested in this analysis. A value of 0.9 produced the optimum results and was used for the final map.

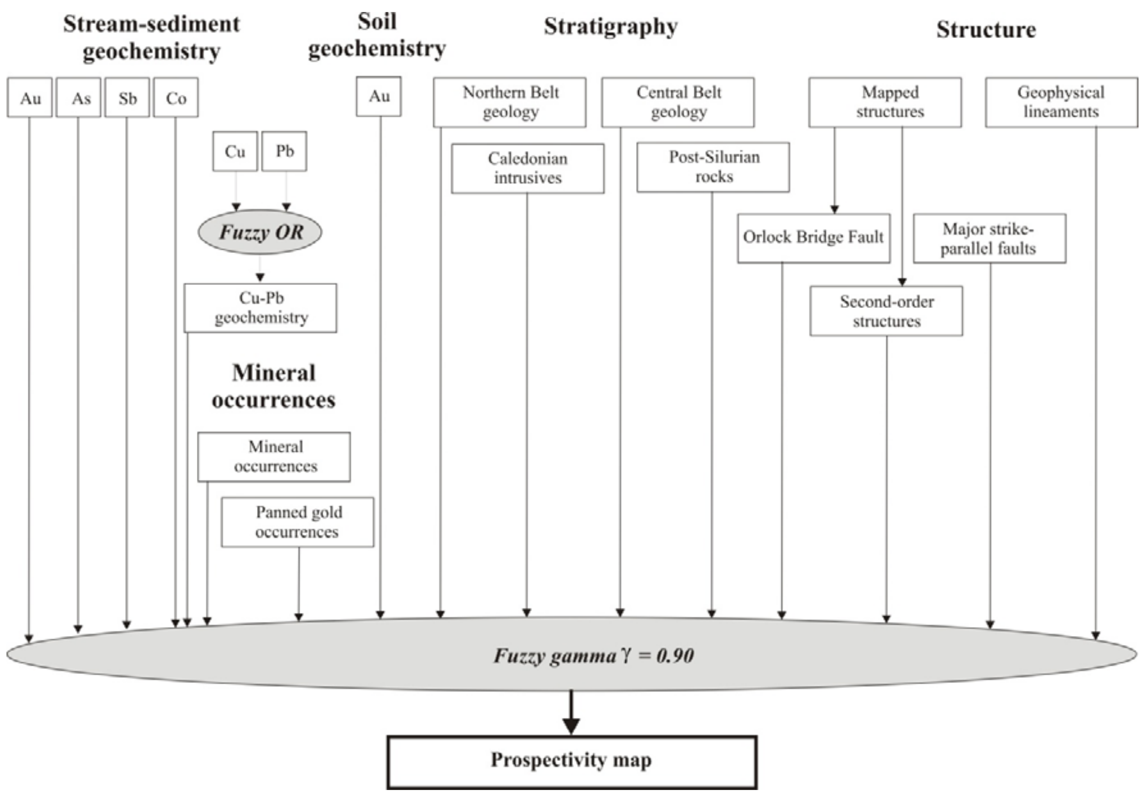

Figure 6. Schematic inference diagram illustrating the combination of evidential themes to form the prospectivity model for vein gold mineralisation in the SULD Terrane.

RESULTS

The results of the prospectivity analysis are shown in Figure 7 and summarised in Table 8. The areas of highest potential were divided into three prospectivity classes; very high, high, and moderate and displayed using a gradational colour scale.

The Northern Belt and the Orlock Bridge Fault zone

The results of the modelling clearly identify the OBF zone as highly prospective with numerous areas of high prospectivity either straddling the fault or located close to it (Figure 7). Straddling the OBF these areas are underlain by a combination of Gilnahirk, Gala and Moffat Shale group rocks. Area A on the western side of the study area is one of the most extensive prospective zones delineated by the modelling, covering approximately 66 km^2. It lies 2 km along strike from the Clontibret deposit and coincides with the Cargalisgorran and Tivnacree gold mineralisation, the most significant bedrock gold occurrences known in the study area (Figure 8). Area A is associated with the maximum recorded gold value (145 ppb) in a soil samples in the study area and one of the highest gold in stream-sediment values (1443 ppb). Four incidences of panned gold were recorded in this area during the Tellus Survey sampling.

Area B, located immediately east of area A, occupies a 30 km^2 zone of very high to moderate prospectivity which is strongly influenced by the OBF. The zones of maximum prospectivity within the area coincide with the intersection of transverse structures with two major strike-parallel faults and the OBF. Area B contains the maximum gold value (1513 ppb) for a stream-sediment sample in any of the target areas, although, gold values in soils are relatively low (<11 ppb).

Area C forms an elongate zone of very high to moderate prospectivity extending for some 10 km at a similar orientation to the regional strike. The northern part of the area is strongly influenced by the OBF and a major strike-parallel fault extends through the centre of the area. This structure is cross-cut and offset by a series of parallel NNE-trending faults. Further smaller zones of very high to moderate prospectivity punctuate the length of the OBF as it extends NE (Figure 7).

Area D, which straddles the OBF, comprises a zone of very high prospectivity to the north of the OBF, and a zone of moderate prospectivity largely to the south. Notably at this point the OBF is offset by around 300 m by a NNW-trending fault. This structure is also intersected by east-west-trending geophysical lineaments.

Area	Approx extent (km^2)	Geology	Maximum Au value in stream sediments (ppb)	Maximum Au value in soils (ppb)	Incidence of gold in panned concentrate	Incidence of mineral occurrences from MOD	Influence of Orlock Bridge Fault	Incidence of major strike-parallel faults	Incidence of other structures
A	66	Northern Belt/Central Belt	1443	145	4	5	High	3	12
B	32	Northern Belt/Central Belt	1513	11	0	0	High	2	8
C	31	Northern Belt/Central Belt	7	3	0	1	High	3	12
D	10	Northern Belt/Central Belt	11	7	0	0	High	1	7
E	70	Northern Belt/Central Belt	52	27	0	2	High	5	12
F	8	Central Belt	111	4	0	0	Mod.	6	5
G	30	Central Belt	10	101	2	0	Mod.	5	11
H	23	Central Belt/Caledonian intrusive	39	7	0	2	None	1	10
I	16	Central Belt/Caledonian intrusive	11	8	0	2	None	2	12
J	60	Central Belt	645	26	0	4	None	2	10
K	41	Central Belt	76	8	0	2	None	2	8
L	12	Central Belt/Caledonian intrusive	35	5	0	0	None	1	4
M	4	Central Belt	4	25	0	0	None	2	3
N	1	Central Belt	8	1	0	0	None	0	0

Table 8. Summary of exploration criteria contributing to the prospectivity of each area displayed on Figure 7. MOD = mineral occurrence database.

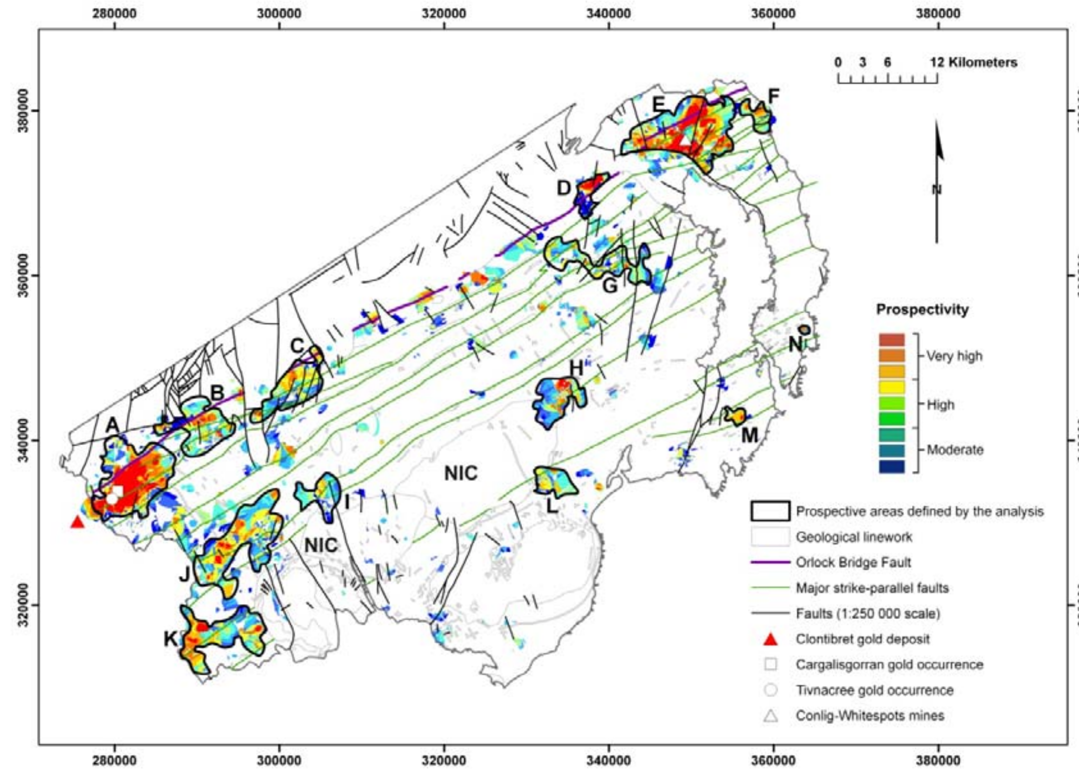

Figure 7. Distribution of prospectivity for Caledonian age, turbidite-hosted orogenic gold mineralisation in the Southern Uplands-Down-Longford Terrane of Northern Ireland. Fuzzy layers were combined using the gamma function, with a gamma value of 0.9. Selected prospective areas defined by the analysis are labelled A–N. NIC = Newry Igneous Complex © Crown copyright and database right (2012) DMOU205.

Area E delineates an extensive (70 km^2) zone of prospectivity located at the northern end of Strangford Loch and is comparable to area A in terms of prospectivity. The area is associated with several soil and stream-sediment gold anomalies. Anomalous arsenic, antimony and base-metal values are also present. The OBF and five major strike-slip faults transect this area and these are intersected by numerous cross-cutting geophysical lineaments (Figure 9). Two mineral occurrences occur in the area including the formerly important lead deposit at Conlig-Whitespots.

Area F (8 km^2) is located on the north-eastern side of the Ards Peninsula along strike from area E. An area of very high prospectivity coincides with a major strike parallel fault and three geophysical lineaments. A minor late Caledonian lamprophyre intrusion is also associated with this zone of very high prospectivity.

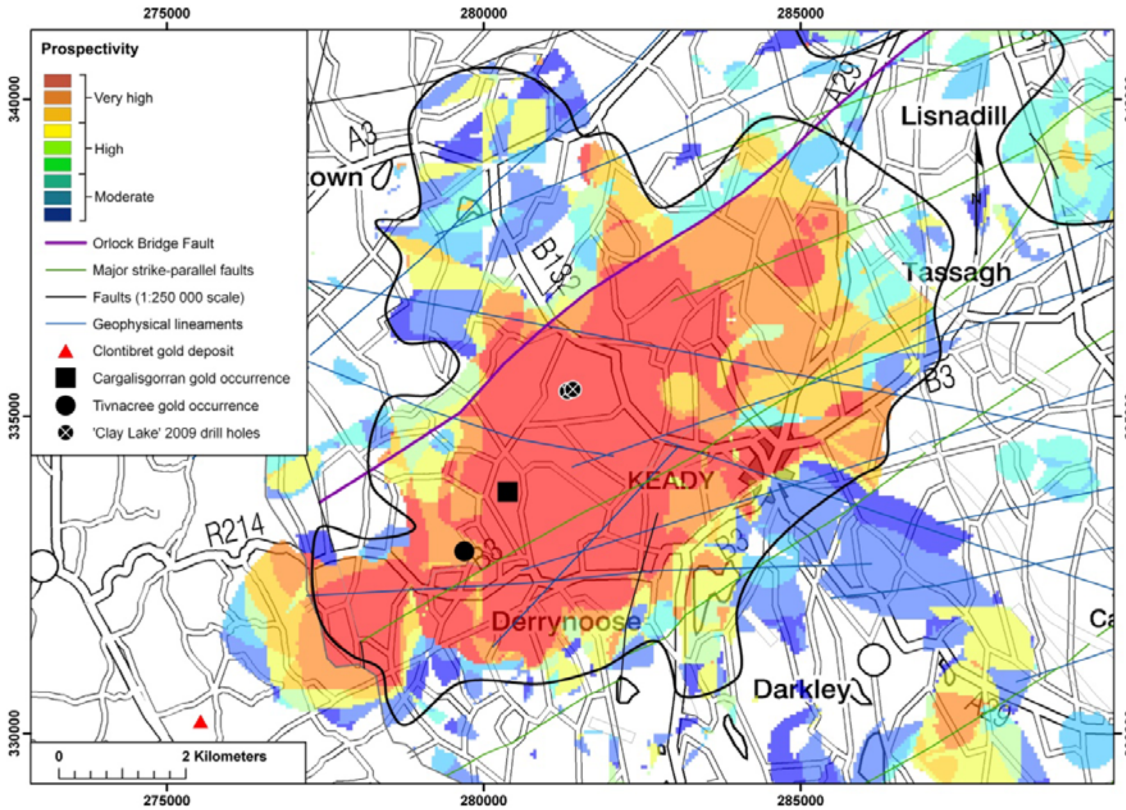

Figure 8. Area A defined by the prospectivity analysis, centred on the town of Keady in south Armagh. Neither the Clontibret deposit, to the south-west, nor the other bedrock gold occurrences were included in the analysis but their coincidence with the zone of high prospectivity supports the validity of the model used © Crown copyright and database right (2012) DMOU205.

Gala Group rocks to the east of the Newry Igneous Complex

Four prospective areas, mainly located in the north-east of the study area, are associated with Gala and Moffat Shale group rocks of the Central Belt. These areas are strongly influenced by major strike-slip faults other than the OBF. Area G starts 2 km south of the OBF and consists of an elongated zone of moderate to very high prospectivity extending for around 13 km east-west. A number of major strike-slip faults extend across the area, intersecting north–south and east–west to north-west-trending transverse structures, a particularly favourable combination for gold mineralisation in the Southern Uplands. The area contains two gold in pan occurrences and a 101 ppb gold in soil anomaly.

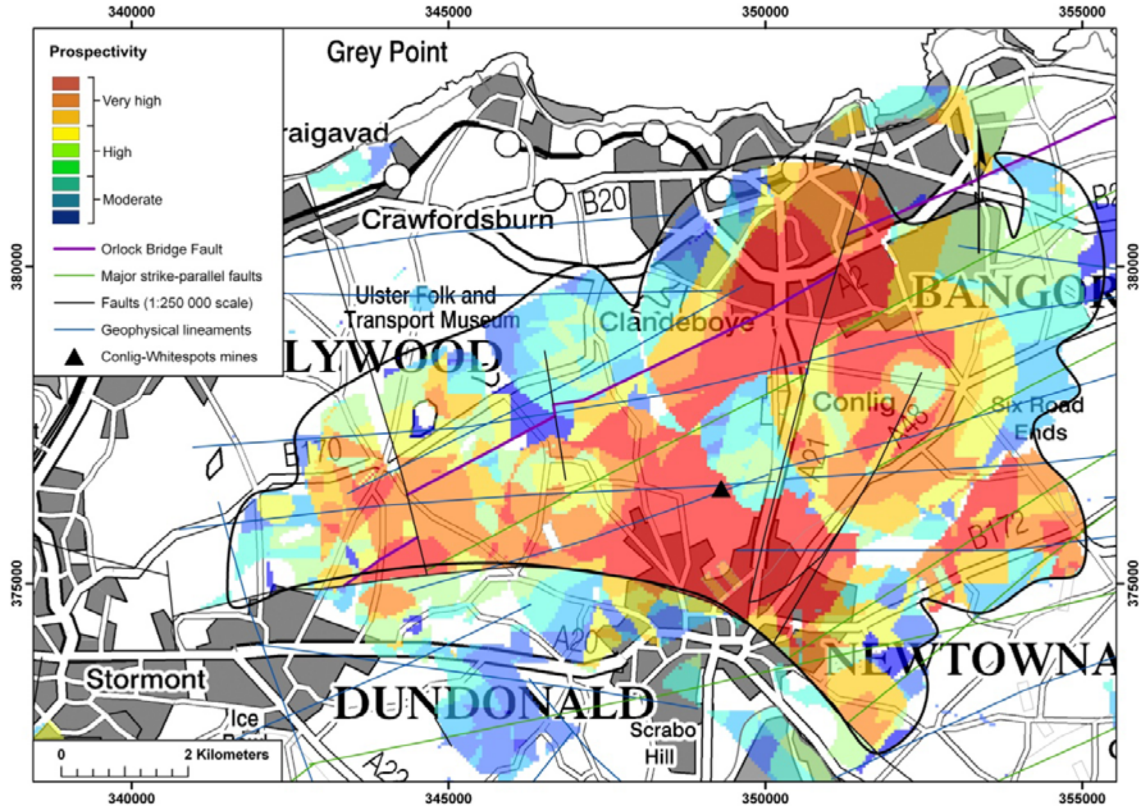

Figure 9. Area E defined by the prospectivity analysis, between Bangor and Newtownards in north County Down © Crown copyright and database right (2012) DMOU205.

Area H consists of a 23 km^2 zone of moderate to very high prospectivity at the eastern end of the NIC. The area is predominantly underlain by Gala Group rocks but extends onto the intrusive complex which comprises granodiorite and local ultramafic-intermediate rocks. A major-strike slip fault transects the centre of the area and is offset by a north-south-trending fault. Additional east-west- to NWW-trending geophysical lineaments intersect these structures and extend into the NIC. Two pyrite-arsenopyrite-pyrrhotite mineral occurrences are located within the area. The maximum gold in stream-sediment value is 39 ppb and two pan gold occurrences are recorded to the south of the area.

Gala Group rocks to the west of the Newry Igneous Complex

Area I extends from the northern contact of the NIC over the surrounding turbidite sequence. A major strike-slip fault transects the centre of the area displaying a minor offset related to a north-south-trending fault, which extends across the entire width of the NIC. Additional east-west-trending geophysical lineaments also dissect the area. Both a pyrite-chalcopyrite and galena occurrence are recorded in the area.

Area J covering 60 km^2 is the third largest target area defined by the prospectivity analysis. It is located on the westward extension of the major strike-slip fault extending through area I, approximately 3 km north of the NIC. The strike-slip fault displays two offsets associated with NNE and NW-trending faults. A geophysical lineament runs parallel to the strike-slip fault. A further NE-trending geophysical lineament extends across the area. Four base-metal occurrences are located within the area, two of which lie between the strike-slip fault and the parallel geophysical lineament. Two stream-sediment samples from the area returned >600 ppb gold and a soil sample with 26 ppb gold is also present.

Area K forms a large area of moderate to very high prospectivity extending westwards from the margin of the NIC. Two zones of high to very high prospectivity can be broadly defined. The easternmost zone borders the NIC and is associated with a pyrite-chalcopyrite occurrence and a 76 ppb gold in stream-sediment value.

Hawick Group rocks

Five prospective areas are evident in the Hawick Group rocks to the south and east of the NIC. Area L straddles the southern contact of the NIC. A major strike-slip fault influences the northern side of the area, with two geophysical lineaments intersecting in the south; otherwise the area has only limited structural control. Area M is a small zone of very high prospectivity located between two major strike-slip faults, coinciding with two sub-parallel geophysical lineaments and a 25 ppb gold in soil value. Numerous late Caledonian lamprophyre intrusions occur within 1 km of the area. Area N, located at the southern end of the Ards Peninsula is situated between two major strike-slip faults, one of which separates Hawick and Gala group rocks. Area N is the only area identified that is spatially associated with abundant late Caledonian lamprophyre intrusions.

DISCUSSION

Prospectivity analysis over the SUDL Terrane of Northern Ireland has identified numerous areas prospective for Caledonian-age, turbidite-hosted orogenic gold mineralisation, comparable to Clontibret and gold occurrences in the Southern Uplands of Scotland. Many of the areas are relatively large, with two exceeding 60 km^2. Nevertheless, the results of the modelling would provide a sound basis for focusing a regional exploration programme and warrant follow-up field surveys. The total area covered by the targets delineated is 472 km^2, representing <13% of the original study area (Figure 7).

Validation of the results of the analysis is important to determine how accurately the exploration criteria have been translated into the prospectivity model. Secondly, it is important to determine the reliability of the results of the analysis in order to assess their predictive capability. Validation of the results is challenging due to the limited number of known bedrock gold occurrences in the study area, coupled with the principal deposit (Clontibret) used for developing the exploration model, lying outside the study area. However, the limited number of known gold occurrences and previous exploration work can be used to provide some indication of the predictive capability of the model.

The model clearly delineates the OBF and environs as being highly prospective, with isolated areas of high prospectivity extending along its entire length. The two most prospective areas A and E coincide with the South Armagh-Monaghan Mining District, centred on the town of Keady in south Armagh, and the Conlig-Whitespots mines between Bangor and Newtownards in north County Down. It is significant to note that area A is located 2 km along strike of the Clontibret deposit (Figure 7). The most significant bedrock gold occurrences identified in the study area are located approximately 5 km along strike from Clontribet at Tivnacree and Cargalisgorran in the ‘Clay Lake’ area (Figure 8). This zone of known gold mineralisation is indicated as highly prospective by the modelling. The coincidence of known gold occurrences (which were excluded from the analysis) with a target generated by the modelling provides validation of the technique. Drilling at Cargalisgorran by Conroy Gold and Natural Resources has identified a mineralised zone extending for at least 150 m and consisting of three steeply dipping, gold-bearing structures, consisting of sulphide bearing quartz-carbonate veins. Mineralised intercepts from the drilling included 6.94 m at 4.14 ppm gold and 9.27 m at 1.88 ppm (Purcell et al. 2007). Mineralisation is thought to be associated with second-order fractures related to the OBF and displays many similarities to the Clontibret mineralisation (Arthurs and Earls 2004). At Tivnacree, 1 km south-west of Cargalisgorran trenching and drilling has identified quartz veining and low-grade gold mineralisation. Drilling to the north-east of these occurrences, by Conroy Gold and Natural Resources, in an area defined as ‘Clay Lake’, has intersected further bedrock gold mineralisation (Figure 8). The high prospectivity of area A is attributed to its close proximity to OBF and the presence of three major strike-slip faults, which transect the area, representing potential corridors for large volumes of fluid migration and a regional structural control on vein development. In addition this area is influenced by numerous transverse structures representing potential local controls on mineralisation.

Indeed many of the prospective areas defined by the modelling are associated with the coincidence of regional strike-parallel structures (either the OBF or other strike-slip faults) and intersecting second-order transverse faults. These structural relationships are considered fundamental in localising auriferous hydrothermal systems in the Southern Uplands (Boast et al. 1990; Leake et al. 1996). Furthermore, the Glendinning deposit in Scotland, which displays many features in common with Clontibret is regarded as being located at the intersection of a series of high angle sinistral faults (Duller et al. 1997). The relationship between the prospective areas and major strike-slip faults was examined to determine whether particular faults appear more prospective. With the exception of the OBF no specific structure appears to be clearly associated with more prospective areas than the others. The first and second major strike-parallel faults located south of the OBF and the two strike-parallel faults to the north of the NIC, transecting areas I and J, have the greatest number of prospective areas associated with them.

Areas E and F have been the focus of previous geochemical exploration programmes for base-metals and E includes the historically significant Conlig-Whitespots mines. It is significant to note that an earlier programme of commercial exploration identified a number of low-tenor gold anomalies in basal overburden samples in this area, with a maximum value of 50 ppb (Grennan, 1989). Limited follow-up sampling in this area was disappointing, returning a maximum gold value of 22 ppb in mineralised samples (Hugall, 2010).

It is important to reiterate that igneous rocks were incorporated in the geological evidence layer solely on the basis that they could provide a suitable depositional environment for gold and are known to host gold mineralisation in association with turbidites in Scotland. The weighting allocated to igneous rocks in this specific model did not attempt to reflect their potential as a heat source for driving hydrothermal systems or as a source of fluids and metals. Given the prominence of the NIC (330 km^2) in the SUDL Terrane, the incorporation of intrusive rocks as an evidence layer in the modelling would inevitably result in a large area of high prospectivity restricted to the NIC and its surroundings. There is no conspicuous prospectivity associated with the NIC or other Caledonian intrusives. This is significant as the Caledonian igneous rocks were allocated the same significance in the modelling as the surrounding metasedimentary rocks. This may be a function of the limited number of structures identified in the igneous complex compared with surrounding metasedimentary rocks, which formed a highly weighted evidence layer in the modelling. Three prospective areas (H, I and L) straddle the contact zone of the NIC. Notably, area H has been the focus of previous exploration campaigns for base metals and gold (Leyshon, 1972). A field survey including panning undertaken in this area concluded that gold is widespread and is related to the intrusion of the Newry Granodiorite (Toal and Reid, 1986). Further work in area H determined extensive zinc anomalies with associated enrichment in arsenic, antimony and possibly mercury. Most significantly a quartz vein sample from this area returned 200 ppb gold (Young, 1987). Work to characterise the gold grains from the Slieve Croob and Hilltown area (coincident with target area H) interpreted most of the gold to be mesothermal shear-zone type (low silver), comparable with gold from the Southern Uplands of Scotland and Mayo (Smith et al. 1996). The most recent phase of exploration carried out over and around the NIC focused on the Slieve Croob area along the northern flank of the complex. Anomalous gold values in stream sediments were widespread and the previously defined arsenic-nickel-copper enrichments were confirmed. Anomalous gold values in bedrock were identified, attaining a maximum value of 77 ppb gold. These were restricted mainly to the siliceous sedimentary rocks close to the intrusive contact with the NIC (Mullin, 2001).

Area I, also spanning the contact zone of the NIC, has been the focus of previous mineral exploration. Panned concentrate sampling revealed visible gold at 15 localities and a maximum gold value in stream sediments of 798 ppb (Toal, 1988). The coincidence in area I of a regional strike-parallel structure intersecting a transverse fault cross-cutting a major igneous body could be significant.

Areas J and K, also in close proximity to the NIC, were the target of previous geochemical exploration (Gregory, 1972). The close proximity of these targets to a granitic pluton is potentially significant as mineralisation in the Southern Uplands commonly occurs in fault zones at the contact between intrusions and country rock. Heat from granitoids could also play a significant role in driving hydrothermal systems within the surrounding country rocks (Naden and Caulfield, 1989). Alternatively the link between gold deposits and intrusions may solely reflect structural anisotropy induced by the stocks during shear deformation (Steed and Morris, 1997). This theory is supported by the observation in area H that gold in bedrock is largely restricted to the sedimentary rocks at the intrusive contact (Mullin, 2001).

Area N is notable as it is the only prospective area distal to the NIC which displays a close spatial relationship with igneous intrusive rocks. Given the apparent lack of other local controls on potential mineralisation in this area the presence of intrusives may be significant. The intrusives are described as Caledonian lamprophyre intrusions. Calc-alkaline lamprophyres are associated with a number of orogenic gold deposits worldwide. It has been suggested that lamprophyres could act as transporting agents for gold from gold-rich sources in the deep mantle, which then undergo extensive crustal interactions, generating felsic magmas or releasing their gold into metamorphic-hydrothermal systems (Rock and Groves, 1988). Shallow and basal overburden sampling at 275 sites north of Portaferry, close to area N, defined a strong lead-zinc anomaly (Grennan, 1989).

The prospectivity analysis supports previous observations that there is no consistent spatial association between gold mineralisation and post-tectonic intrusions across the Southern Uplands (Gunn and Plant, 1998). However, a separate model would be required to examine potential for mineralisation genetically associated with granitic rocks in the SUDL Terrane.

In modelling of this type the delineation of prospective areas specifically for Caledonian orogenic gold mineralisation is complicated by the potential influence and interference of later mineralising processes. For example, in area H the geochemical data and its significance in the model must be treated with caution as there is potential for the anomalies to be associated with the widely developed Palaeogene dykes. In addition a cluster of three highly anomalous, gold values in stream-sediment samples is present over the outcrop of Hawick Group rocks on the south side of the Eastern Mournes Centre of the Palaeogene Mourne Mountains Complex. These values could reflect dispersion of gold from the granite bedrock of the Mourne Mountains (Flight and Lister, 2009). This study has not identified any prospective areas within the Mourne Mountains Complex, suggesting that features of the model critical for older Caledonian mineralisation are absent, although significant gold values are present.

CONCLUSIONS

Regional scale prospectivity analysis over the SUDL Terrane of Northern Ireland using a fuzzy logic approach, integrating new geochemical and geophysical data, has identified several areas prospective for turbidite-hosted orogenic gold mineralisation, comparable to Clontibret and gold occurrences in the Southern Uplands of Scotland. A number of these either coincide with known bedrock gold occurrences or with areas considered prospective and targeted by previous exploration work, validating the predictive capability of the exploration model devised and its translation into a GIS-based prospectivity model. The knowledge driven, fuzzy logic approach used in this study requires a quantitative knowledge of the key geological controls on the style of mineralisation being targeted. A comprehensive understanding of the mineral type being sought is fundamental to the selection and derivation of evidential themes which in combination may be indicative of mineralisation. The results of the modelling suggest that, as in other parts of the Southern Uplands, the coincidence of regional strike-parallel structures and intersecting transverse faults are highly prospective, as these are likely to create zones of anomalous stress for fluid flow and deposit formation. Those areas in which there are no known gold occurrences are considered to be favourable targets for further exploration and should be followed up. It has long been recognised that integration of multiple geoscience datasets is advantageous for mineral exploration targeting. This technique would appear to be a cost-effective, desk-based regional exploration tool, when regional exploration datasets are available. This is demonstrated by the total area covered by the targets delineated, representing less than 13 per cent of the original study area. It is likely that refinement of the exploration model, including incorporation of additional criteria, supported by appropriate datasets, would improve the reliability of the results and more closely define the targets. The results of the modelling suggest that the exploration criteria have been successfully translated into the model and similar criteria could be used for prospectivity analysis in comparable terranes elsewhere. The approach described for Northern Ireland could be applied to the Southern Uplands of Scotland, for which comparable datasets are available.

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