Prospectivity of tungsten in South-West England using Bayes' Theorem

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Bayes' theorem of conditional probabilities is used to evaluate the potential for tungsten mineralisation in the granites and surrounding country rocks of the southwest peninsula of England. The approach uses the distribution of known tungsten mineralisation in relation to geological controls that can be mapped, to calculate the probability by unit area of as yet undiscovered mineralisation. It permits the evaluation of the efficiency of the chosen exploration criteria one by one and in combination. The method indicates areas of up to 20 km^2 where the posterior probability of a square kilometre containing tungsten mineralisation approaches unity, located in a discontinuous zone extending from the east side of the Godolphin Granite in the south, through the eastern margins of the Carn Marth Granite to St Agnes and Cligga Head with small outliers elsewhere on or close to the outcrop of the southwest granites.

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Introduction

The southwest peninsula of England has been an important source of metals since ancient times. Tin was the main commodity sought for most of this time and by the late 19th Century accounted for half the world production (Dines, 1956, p.21). Mining of copper also has ancient origins but did not become important until the 19th Century when for a short time in the 1850s Devon and Cornwall supplied 40 per cent of world production. Since those times, there has been a decline such that at the present time, there are no working base metal mines in the region. There is however in the current world market conditions, renewed interest in tin and tungsten mineralisation. Most notably, planning and environmental permits to reopen the tungsten-tin mine at Hemerdon Ball have been negotiated and finance raised, and redevelopment of the mine is now under way with production expected in the third quarter of 2015.

Tin and tungsten mineralisation in the region are genetically and spatially related to the intrusion of the Cornubian granites (Figure 1). The following sections attempt to use the wealth of mineral distribution and geological data for this area to draw conclusions about where further occurrences of tungsten might be sought. The method used is based on Bayes' theorem of conditional probabilities (Bernardo and Smith, 1994), applied to mineral exploration by Bonham-Carter and colleagues at the Geological Survey of Canada in the 1980s (Bonham-Carter *et al.*, 1988) and has subsequently been used by others for mineral exploration applications (Barr, 1990; Raines, 1999; Deng, 2009; He *et al.*, 2010; Pazand and Hezarkhani, 2013).

Method

Bayes' theorem relates the odds or probability of an event given that it satisfies some condition, to its unconditional probability through other parameters that can be measured. Expressed algebraically:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \qquad (1)$$

where P(A|B) is the probability that A occurs, given that condition B is satisfied, P(B|A) is the probability that B occurs given that condition A is satisfied and P(A) and P(B) are the unconditional probabilities of A and B respectively (Bonham-Carter *et al.*, 1988). Applied to mineral exploration, the relationship may be restated as:

'the probability that a unit area is mineralised on condition that it satisfies some aspect of relevant mineral exploration data, is given by the product of the proportion of unit areas where this condition holds that are mineralised (P(B|A)) and the unconditional probability of mineralisation (P(A)), divided by the proportion of the whole exploration area where the condition applies (P(B))'.

P(A) is referred to as the prior probability of mineralisation, i.e. the probability before considering any exploration data. P(A|B) is the posterior probability given that the area identified satisfies some criterion of the exploration data B. P(B|A) is not known for sure unless every mineral occurrence has been identified, in which case the exercise would be pointless, but it can be estimated from the distribution of known mineral occurrences.

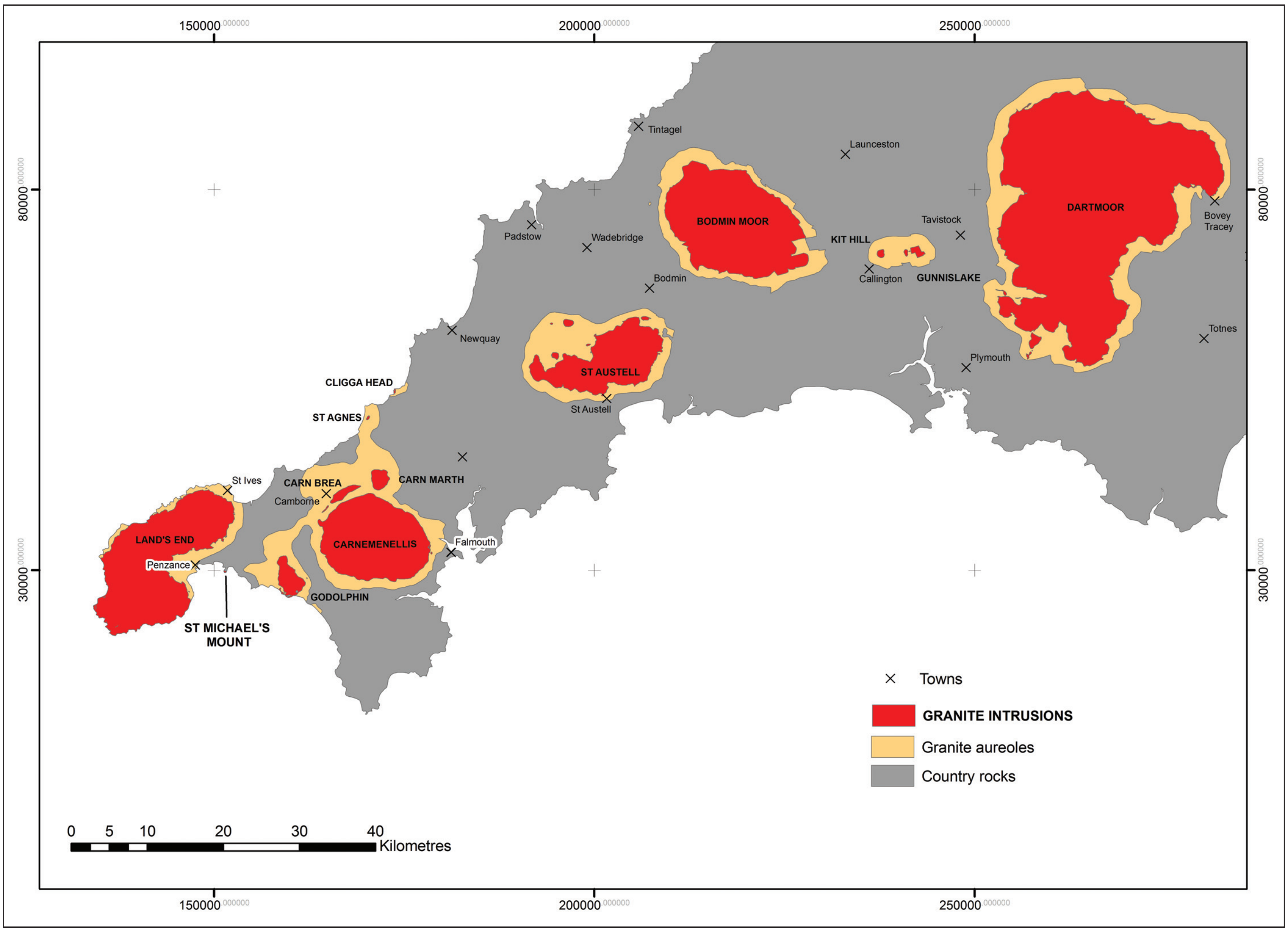

Figure 1. *Study area and outline geology.*

It can also be shown that the posterior odds are given by:

$$exp\{\ln(O(A)) + \Sigma(w^{k_j})\} \qquad (2)$$

where O(A) are the prior odds of a unit area being mineralised, i.e. the odds before considering any exploration data patterns, and W^k_j is a weight derived from Equation (1) for the k^{th} exploration data set out of j sets (Bonham-Carter *et al.*, 1988). The posterior probability can be simply calculated from the posterior odds but the weights are themselves of perhaps greater interest since they indicate the power of discrimination of a set of exploration data between areas likely to be mineralised on the one hand and the those not on the other, without reference to the prior probability of mineralisation. The significance of the weights is recognised by the term 'weights of evidence method' which is sometimes used for this approach. Note that the weights are additive; it is possible to create a set of maps divided up into prospective and non-prospective areas with an attribute w, assigned values W+ for prospective areas and W- for the balance of the exploration area. By adding these maps together, a final map is produced showing the outcome of consideration of several independent sets of exploration data. The exploration data need not be coincident. Where data are missing, the related weight applied is zero and has no effect on the evaluation of Equation (2).

The calculation involved has been implemented in Visual Basic (VB) for the ArcGIS suite of geographic information system (GIS) programs (see also Bonham-Carter and Agterberg, 1999). The VB code developed for ArcView 9.2 running on Windows 7 is available on request but no warranty is provided that it will work properly on any platform/operating system/ArcGIS version combination (see also Kemp *et al.*, 2014). Figure 2 illustrates the outcome of one run of the software. It is divided into a set of steps. The text box of Step 1 lists the attribute fields of the second-to-top layer in the GIS from which the user selects one where the attributes of possible exploration interest are stored. In this case, the field is called 'strat' and stores the names of the different stratigraphic units used to draw the map, based on British Geological Survey (BGS) geological mapping.

The list box of step 2 lists the different categories in the stratigraphy field. By using the direction arrows, the user can refine the selection of categories (of stratigraphy in this case)

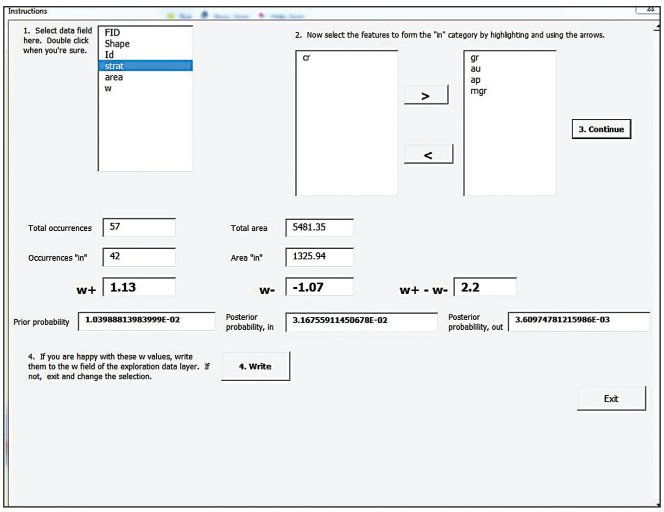

Figure 2. *Form that controls the steps of the Weights of Evidence method and shows the results (cr = country rock, gr = granite, au = thermally metamorphosed rocks of the granite aureoles, ap = aplite, mgr = microgranite). See text for full explanation.*

that define the area to be selected as the more prospective to be coded W+ in the output. In the example, all types of granite and the granite aureoles are selected; only the country rocks are left out of the prospective area. Step 3 populates the text boxes towards the bottom of the form. In those cases where the selection is considered optimal, usually either when W+ or W+ - W- (Wdiff) is a maximum, the user may proceed to Step 4 which writes a new map of the exploration area divided into three categories, one part with w attribute W+, one W- and one coded with W=0 applied to those parts not covered by or deliberately excluded from the exploration data. The last step of combining these maps by adding the values in the w attribute to create the final output uses the standard map algebra functions of the commercial software package.

MINERAL OCCURRENCES

Table 1 lists the mineral occurrences used for the study and Figures 3 and 4 show their distribution. The entries in Table 1 are mainly taken from pages 33-57 in Dines (1956) with further

ID	District	Name	Tin	Copper	Arsenic	Tungsten	Others	Production main resource (tons)	Stockwork ?	Tier
1	St Austell	Bunny	1			2	Cu, As	700	False	2
2	St Austell	Castle-an-Dinas			2	1		3,000	False	1
3	St Austell	Stennagwyn	1			2	U		False	2
4	St Austell	Maudlin		1		2		110	False	2
5	St Austell	Mulberry	1					1,350	True	2
6	Wadebridge	Buttern Hill	2			1			False	2
7	Wadebridge	Highmoor	1			2			False	2
8	Liskeard	Cannaframe	2			1		0.5	False	2
9	Liskeard	Halvanna	1			2			False	2
10	Liskeard	Herodsfoot		3		4	Pb,Ag		False	2
11	Liskeard	Trebartha-Lemarne	2		1	4	S	20	False	2
12	Liskeard	Treburland	1			2			False	2
13	Liskeard	Vincent	1		2	3		62	False	2
14	Callington	Dimson				1			False	3
15	Callington	Downgate Consols	2			1	As	10	False	3
16	Callington	Drakewalls	1	3	2	6	Pb, Ag, Mo	5,433	False	2
17	Callington	Friendship	6	1	2	8	S, Zn, Pb, Ag	42,900	False	2
18	Callington	Gunnislake Clitters	2	1	4	3			False	2
19	Callington	Hawkmoor	2	1		4	S	3,559	False	2
20	Callington	Hemerdon Ball	2			1			True	1
21	Callington	Hingston Down	4	1	3	2			True	3
22	Callington	Holmbush	1	2		5	Pb, Ag, F	42,900	False	2
23	Callington	Jewel	1		2	3			False	2
24	Callington	Kit Hill United	1	3	4	2			False	2
25	St Austell	Old Beam	1			2			True	3
26	St Austell	North Bunny	1						False	3
28	St Austell	South Polgooth	1				Cu, As		False	3
29	Liskeard	Trezelland and Blackadon							False	3
30	Liskeard	Hawk's Wood							False	3
31	Liskeard	Stanbear Cott							False	3
32	Liskeard	Pheonix United							False	2
33	Liskeard	Penhale							False	3
34	Liskeard	Treveddoe					Cu, Sn		False	3
35	Liskeard	Gazeland							False	3
36	Liskeard	Gazeland							False	3
37	Callington	Kelly Bray					As, Cu		False	3
38	Callington	Redmoor							False	3
39	Callington	Redmoor					Mo, Pb, As		False	3
40	Callington	Kit Hill United							False	3
41	Callington	Excelsior							False	3
42	Callington	West Prince of Wales							False	3
43	Callington	Silver Valley							False	3
44	Callington	Hingston Down, Plantation lode							False	3
45	Callington	Wheal Arthur					Cu, As		False	3
46	Callington	Consolidated Tamar Mine					Cu, As, Sn		False	3
47	Callington	East Calstock							False	3
48	Callington	New Great Consols					Cu, As, Sn		False	3
49	Callington	Benny					Sn, As		False	3
50	Callington	Frementor					Sn, As	12,000	False	3
51	Callington	Bedford United					Cu, As, Sn	65,950	False	2
52	Callington	Ding Dong					Sn, As, Cu		False	2

Table 1. *Tungsten mineral occurrences used for the study. See text for explanation.*

occurrences and added information from other sources (Hill *et al*., 1906; Jackson and Rankin, 1976; Kettaneh and Badham, 1977; Maclaren 1917; Manning, 1983; Scrivener *et al*., 1977 and Ward, 1983). The entries in Columns 4 through 7 are from Dines. They show the ranking of the resources won at each mine with significant tungsten production (those where tungsten is also ranked) where known. The entries in the column headed 'Others' are the chemical symbols of the metals that accompany tungsten not shown in the columns 'Tin' to 'Tungsten', with the exception of umber and pyrite (Py). The production column records the total tonnage of the main resource produced as a guide to evaluating the importance of each mine for former tungsten production. Where the resource is not ranked in the columns 'Tin' to 'Tungsten', then the production relates to the first element in the 'Others' column. Each mine or occurrence was represented initially by one point on the mineral occurrence map. If the deposit from which the tungsten came is mentioned in the text, then the occurrence is located on or near it. Otherwise, it is shown at an approximate location within the mine area identified from Dines' maps, Ordnance Survey mapping at 1:10,000 scale (StreetView) and reference to Google Earth aerial photographs.

ID	District	Name	Tin	Copper	Arsenic	Tungsten	Others	Production main resource (tons)	Stockwork ?	Tier
53	Callington	South Bedford					Sn, As		False	3
54	Callington	North Impham					Sn		False	3
55	Callington	Gawton					Cu, As, Sn		False	3
56	Callington	Florence					Sn		False	3
57	Callington	West Sortridge Consols					Sn, As		False	3
58	Callington	Roborough Down							False	3
59	Liskeard	Tregune							False	3
60	Callington	Wheal Conquer					Cu, Zn, pyrite		False	3
61	Callington	Trevell					Pb		False	3
62	St Agnes	Cligga Head	2			1		300	True	1
63	St Agnes	Droskyn	2	1		3	Umber	1.5	False	2
64	St Agnes	Good Fortune	1	2		3		0.5	False	2
65	St Agnes	Perran St George	3	1		6	S, Zn, Pb		False	2
66	Camborne	Busy	3	1	2	5	S, Pb, Ag		False	2
67	Camborne	Carn Brea and Tincroft	2	1	3	4	Pb	390	False	2
68	Camborne	South Crofty	2	1	3	4	F,S	1379	False	2
69	Camborne	Little North Downs	2	1		3		29,848	False	2
70	Camborne	Gorland	3	1	4	2	F	40,750	False	2
71	Camborne	Park-an-Chy	1			2	As, F		False	2
72	Camborne	Poldice	2	1	3	4	S, Zn, Pb		False	2
73	Camborne	East Pool and Agar	2	1	3	4	U, Co ,Bi, Ni	2,820	False	1
74	Camborne	St Day United	2	1	3	4	S, Zn, Pb Ochre, F		False	2
75	Camborne	Wheal Peevor					Sn		False	2
76	St Just	Levant	2	1	3		Ag		False	3
77	St Just	Baleswidden	1				Bi, F	11,828	True	3
78	Gwinear	Rosewarne and Herland					Cu,Sn,Zn,As,Ag	30,000	False	3
79	Gwinear	Relistean					Cu, As	12,150	False	3
80	Gwinear	Nancegollan					Sn,Py,F,Zn,Cu	6	False	3
81	Mounts Bay	Prospidnick					Sn	25	False	3
82	Mounts Bay	Great Fortune					Cu, As, Py, Zn	2,569	True	3
83	Mounts Bay	Great Work					Sn, Cu, As, Py	6,256	False	3
84	Carmenellis	Balmynheer					Sn, Zn	27	False	3
85	Camborne	New Roskear Shaft					Sn, As, Cu,		False	3
86	Camborne	North Dolcoath					Ag, Cu, Sn	43	False	3
87	Camborne	Dolcoath					Cu, Sn, S, Zn, Ag, Bi, As, Co, Ni	80,000	False	3
88	Camborne	Carn Brea and Tincroft					Cu, Sn, As		False	3
89	Camborne	South Crofty					Cu, As, Sn		False	3
90	Camborne	South Carn Brea					As, Sn		False	3
91	Camborne	Little North Downs					Cu, Sn, As, Zn	29,848	False	2
92	Camborne	Treskerby					Cu, Sn		False	3
93	Camborne	Great North Downs							False	3
94	Camborne	Scorrier Wolfram							False	3
95	Camborne	Wheal Rose							False	3
96	Camborne	Hallenbeagle							False	3
97	Camborne	Killifreth					Cu, Sn, Mo, As, Py, Zn		False	3
98	Camborne	United Mines							False	3
99	Callington	Hingston Down Quarries							False	3
100	Camborne	Mount Wellington							False	3

Table 1 continued.

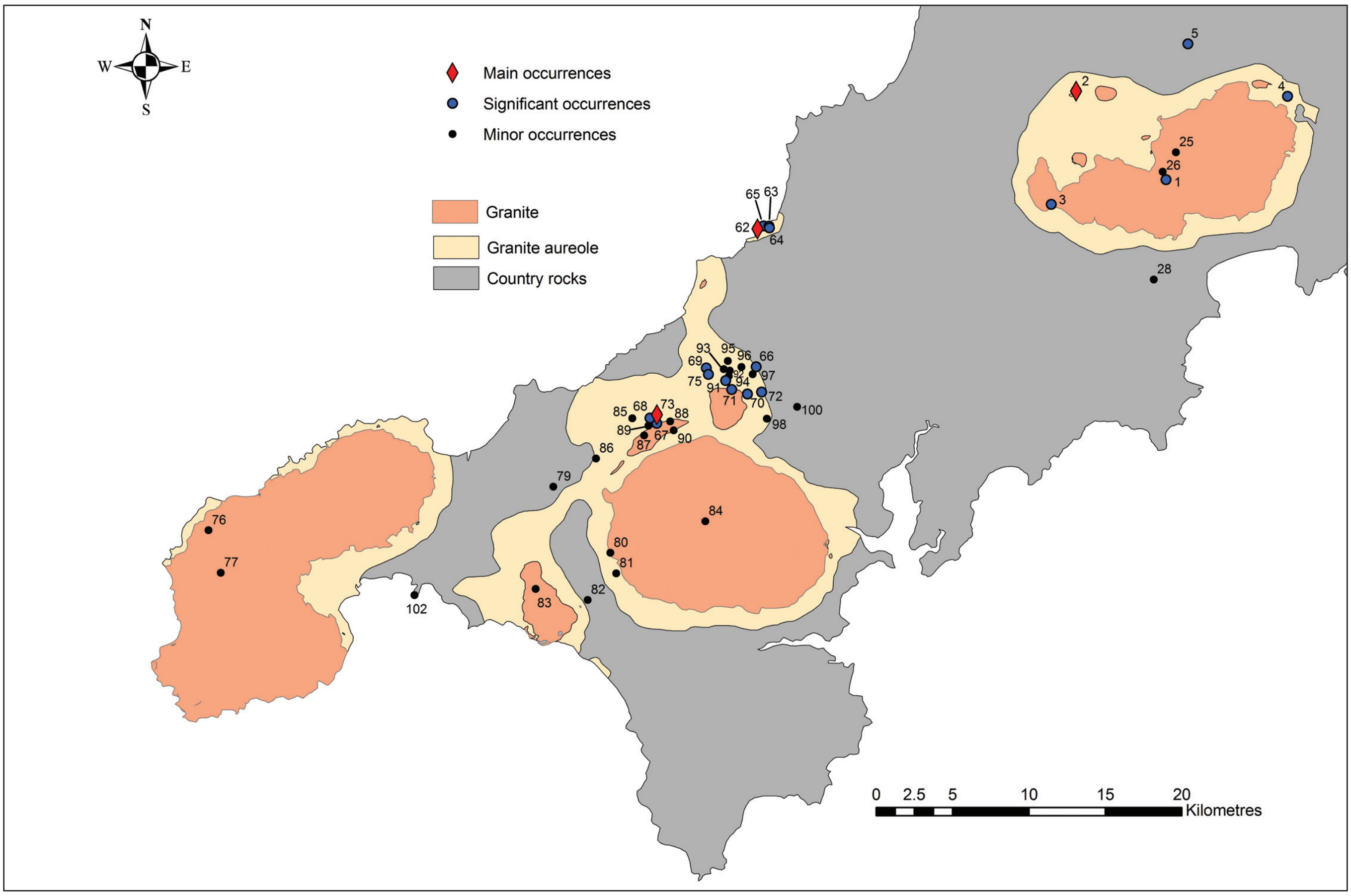

Figure 3. *Distribution of tungsten occurrences (west). Numbers refer to the entries in Column 1 of Table 1.*

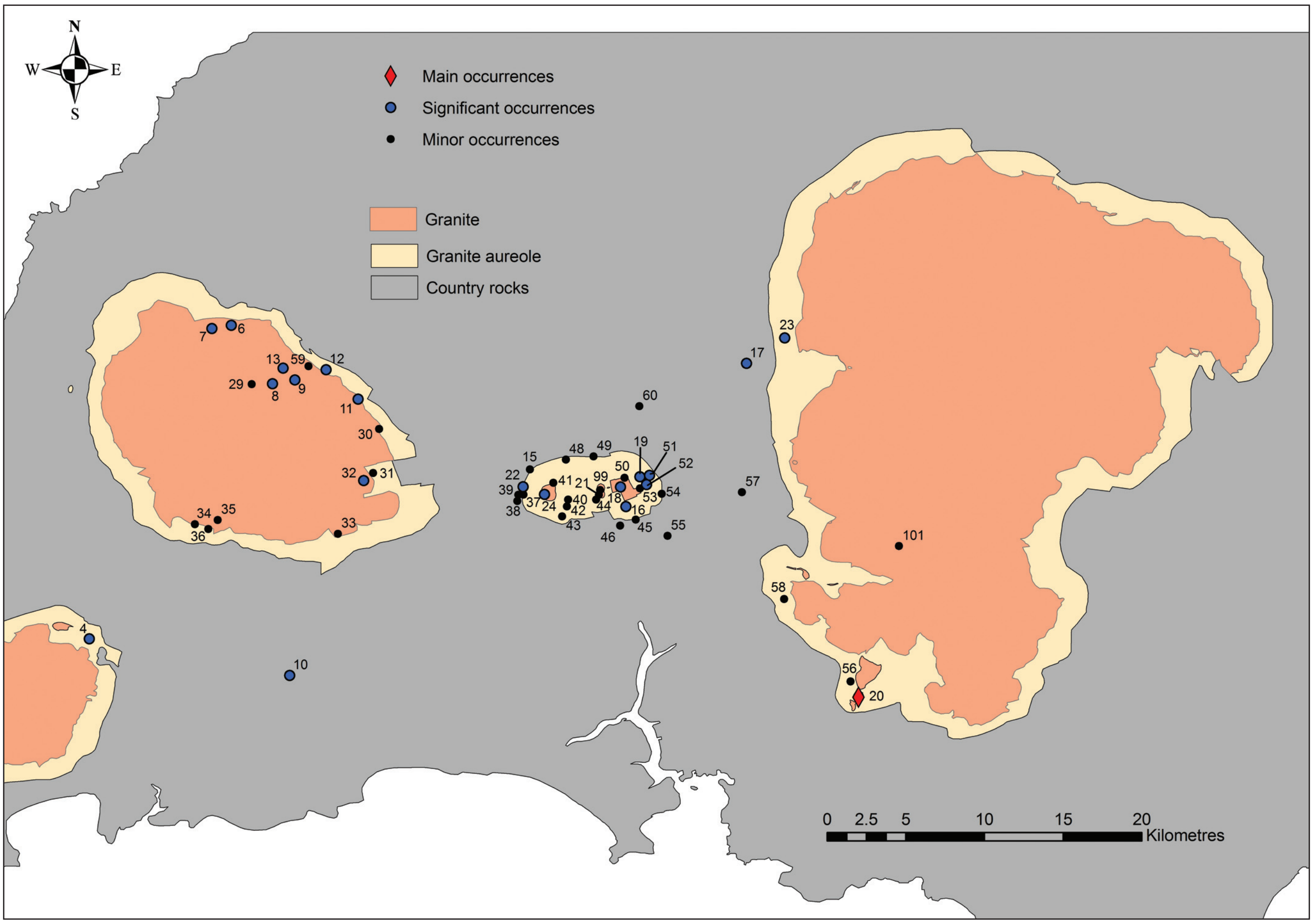

Figure 4. *Distribution of tungsten occurrences (east). Numbers refer to the entries in Column 1 of Table 1.*

The occurrences have been assigned to one of three tiers. Tier 1 refers to major tungsten occurrences (main occurrences of Figures 3 and 4) of which only four are marked. Hemerdon and Castle an Dinas are significant tungsten prospects in their own right. To them have been added further occurrences at East Pool and Agar and Cligga Head where there has been significant tungsten production in the past. Tier 2 (significant occurrences of Figures 3 and 4) refers to entries in Dines' table where tungsten is identified as a metal that was formerly produced plus a few others described in the text that appear to be more than mere occurrences. Tier 3 refers to the balance of occurrences.

Most of the evaluation of the method has been carried out using these selections. However, the evaluation of Equation 1 is based not on mineral occurrences but on mineralised unit areas. The unit chosen for the study was 1 km^2, partly because it simplifies the calculations involved and partly because an area of about this size could reasonably be the target for further more detailed exploration. In order to convert occurrences to areas, those that fall within the same square kilometre tile are represented by a single point drawn approximately at their centroid on a revised mineral occurrence map used to generate the final outcome of the study.

Finally, Moore (1977) and Charoy (1981) point out the commercial advantages, from a mining point of view, of working mineralised sheeted vein complexes by bulk extraction from open pits, such as Hemerdon, rather than single veins or lodes, accessed by deep mining. The sheeted vein complexes cited by these authors that are also known to contain tungsten mineralisation (penultimate column of Table 1) were therefore subject to a separate series of tests to see if they have a different set of controls from other groupings of mineral occurrences.

EXPLORATION CRITERIA

Tungsten mineralisation in South-West England is generally understood (Jackson *et al.*, 1989; Alderton, 1993; Scrivener, 2006) to have occurred in the early stages of granite-related mineralisation, and, in most cases, to be developed within the granite bodies, or in the proximal parts of the host rocks. The style of tungsten occurrences shows some variation, with examples including flat-lying pegmatitic bodies (e.g. the 'quartz floors' of South Crofty Mine), single steeply dipping hydrothermal veins (e.g. Castle-an-Dinas Mine) and, most notably, the large sheeted vein complexes such as Cligga Head and Hemerdon. In the Gunnislake - Kit Hill district, wolframite is present as an early phase in complex polymetallic veins carrying, in addition, tin, copper, arsenic and lead (Beer and Scrivener, 1982). A notable feature of most tungsten-bearing veins is the association with wallrock greisen alteration. In the case of granite host rocks, this involves the formation of assemblages including quartz and white mica +/- topaz. The links between tungsten deposits, greisen alteration and the earliest stages of mineralisation have been established by a number of metallogenetic studies including those of Jackson *et al.* (1977), Charoy (1981) and Darbyshire and Shepherd (1987).

The relationship of tungsten mineralisation to the mapped lodes is obvious from existing mapping of mineralised areas and the pattern of lodes was used to identify zones where further mineralisation might be concentrated. However, the approach can be criticised firstly because the location of the lodes on the geological map is the direct result of mineral exploration. Their mapped distribution is not independent of the known mineralisation; it reflects more where exploration has been carried out than the actual distribution of lodes. The coincidence is objectionable both from a theoretical point of view but also practically - it is quite unlikely that further mineralisation will be found where so much work has already been carried out. This objection would have great force if tin were the resource being sought. It is perhaps less strong in the case of tungsten, the known distribution of which appears less strongly correlated with past exploration and exploitation effort.

A notable feature of some tungsten occurrences in South-West England is the association with north-south trending lineaments. In the case of Hemerdon and Cligga Head, the host granites are north-south elongate and the Castle-an-Dinas lode, to the north of the St Austell Granite, also has that trend. To the west of Castle-an-Dinas, there are extensive north-south trending geochemical soil anomalies, parallel with late-stage iron lodes (G.S. Camm pers. comm.). Late-stage veins of north-south trend 'crosscourses' are widely developed in South-West England and while many are barren others carry iron ores or lead-zinc-silver mineralisation. The latter mineralisation has been demonstrated to be of Triassic age (Scrivener *et al.*, 1994; Leveridge *et al.*, 2002), but it is clear that these fractures have a longer history of movement and mineralisation (e.g. Shepherd and Scrivener, 1987). A possible example of early and late mineralisation within a north-south trending system is Herodsfoot Mine, to the south of the Bodmin Moor pluton, which recorded the production of tungsten concentrate in addition to lead-silver ores.

Dines (1956) and others (e.g. Dearman and Sharkarwi, 1965) have drawn attention to the importance of 'emanative centres' in determining the location of lodes and the minerals that they contain; Dines (1956, figures 3a and b) has produced a map showing the distribution of these centres. They could be used as one of the controls on tungsten mineralisation. However, they are derived from and almost exactly mimic the distribution of mineralised lodes so the latter were used directly and are preferred as a guide to so far undiscovered mineralisation.

From a fluid migration point of view, one might expect mineralisation to be concentrated in and around the upper parts of the granite bodies. It is now generally accepted that this is the case, and it is clear that granite cupolas and bosses especially, are favourable sites for tungsten mineralisation (e.g. St Michael's Mount, Cligga Head, Kit Hill and Hemerdon). A map of the depth to the top of the granite has been prepared by the BGS (B. Chacksfield pers. comm.). However, it does not extend very far from the main granite bodies. Detailed gravity data have also been interpreted in terms of depth to the granite surface for the southwest part of the Dartmoor granite (Tombs, 1980) but here also, it applies to only part of the area of study. The gravity field was therefore used as a proxy for depth to the granite contact on the basis that the granite is less dense than the country rocks and highs in the granite surface are represented by gravity lows.

In summary, the following exploration criteria were tested for their efficiency in predicting where undiscovered tungsten mineralisation should be sought:

1) Geological units; Dines (1956) notes that the mineralisation seems to be unaffected by the nature of the envelope rocks except that wolfram may be replaced by scheelite in greenstone bands. The geological units used, individually and in combination, were the different kinds of granite shown on BGS maps, the thermal aureoles and the country rocks outside the aureoles.

2) Proximity to the granite contact; proximity zones symmetrical about the granite contact were used.

3) Lode density expressed as length per unit area; the lodes shown on the BGS 1:50,000 scale mapping were used; while not identical, they closely correspond to the lodes shown on the maps in Dines (1956). The software used restricts the output to the extent of mapped veins; the margins of the project area were therefore not assigned a vein density class and, during subsequent calculations, were assigned a weight (W) of zero.

4) Density of crosscourse lodes using the same calculation method as for all BGS lodes; these were abstracted from the BGS mapping supplemented by crosscourses shown on Dines' maps but absent from the BGS data. Note that crosscourses that are now known to be associated with mineralisation at Hemerdon and Cligga Head were not included.

5) Gravity lows in the envelope rocks; the Bouguer gravity at observation stations within the study area were copied from the BGS website; dummy values were added just offshore so as to constrain the calculated onshore gravity field near the coast during interpolation. A regular grid of gravity values on 100 m centres was created using a cubic spline interpolation that produces a smoothly varying gravity field that honours the data points. A gravity slope map (first horizontal derivative) was created from the gravity map along with a contour map of the onshore gravity field. The slope map was divided into 32 slope categories. Categories with zero and low slope were divided into those believed to represent the crests of granite cupolas in the subsurface and those representing depressions in the granite surface; the latter were masked out using the contoured gravity as a guide. The Weights of Evidence program was run on the balance using progressively steeper slope categories to define the 'in' area.

RESULTS

Vein density (length of vein per unit area) was calculated using a distance weighted algorithm that gives greater influence to veins closer to the output cell centre, and a circular search radius of 1,500 m (Figure 5). The search radius is a compromise between achieving adequate coverage by the lower density classes and retaining enough detail in the higher ones. The output cell size is 100 m square. The continuous density map was quantised into 32 density classes of equal width (Class 32 is the most dense, Class 1 the least) and converted to a shape file for input to the Weights of Evidence program.

The program was run starting with the class representing the densest distribution of veins and repeated including progressively less dense classes (Table 2 and Figure 6). Reference to Figure 6 shows a typical pattern of variation of the weights. No occurrences are included close to the maximum concentration of veins and it is not until Category 15, corresponding to all the vein density classes from 32 to 16 and covering an area of 26.84 km^2, that one occurrence is included in the 'in' area. As more density classes are added and the area 'in' is increased, so the number of occurrences in the 'in' area also increases, as does W+. At some point in this progression, the rate at which occurrences are added to the 'in' area falls off because they are more sparsely distributed away from vein concentrations, and W+ starts to fall. During these changes, W- shows a steady decrease. This is modest because of the inclusion of large areas where there are no tungsten occurrences.

The choice of the 'best' range of density categories is a matter of a trade-off between several considerations. Selecting a density category where Wdiff is maximised might be considered to offer the best opportunity of identifying the areas where the chances of finding more mineralisation are maximised while, at the same time, minimising the chances of missing significant mineralisation in the areas left out. Selecting a density category where W+ is at a maximum would be driven by similar considerations but ignores the opportunities lost by excluding mineral occurrences that fall outside the identified area. A further consideration is the size of the area identified as prospective; in real life, a balance no doubt would be struck between the chances of finding further mineralisation indicated

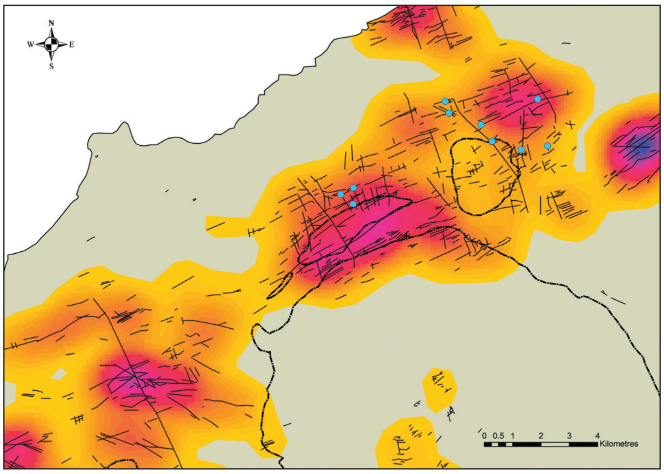

Figure 5. *Part of the vein density map centred on Carn Brea. Lowest density class in grey, progressively higher classes in shades of yellow, magenta and blue. Thick broken line = granite margin, narrow black lines = veins, blue circles = tungsten occurrences (Tiers 1 plus 2).*

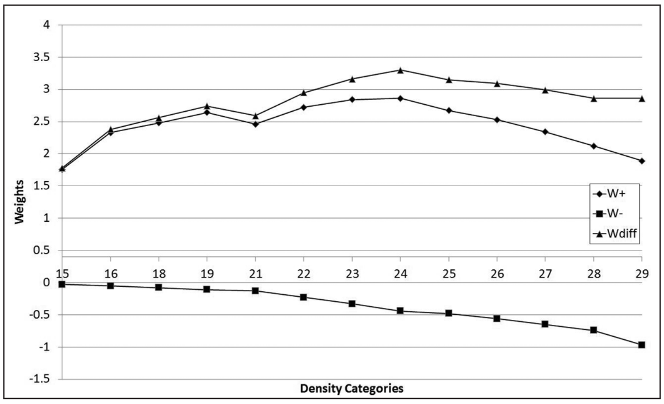

Figure 6. *Weights of Evidence for the vein density categories of Table 2.*

Density classes	Density categories	Total occ.	Total area (km^2)	Occ. 'in'	Area 'in'	W+	W-	Wdiff.	Prior prob.	Post prob. 'in'	Post prob. 'out'	Exp(W+)
32-16	15	38	5762.82	1	26.84	1.76	-0.03	1.78	0.0066	0.037	0.0065	5.8
32-15	16	38	5762.82	2	31.08	2.33	-0.05	2.38	0.0066	0.064	0.0063	10.3
32-13	18	38	5762.82	3	40.67	2.48	-0.08	2.56	0.0066	0.074	0.0061	12.0
32-12	19	38	5762.82	4	46.77	2.64	-0.11	2.74	0.0066	0.086	0.0059	14.0
32-10	21	38	5762.82	5	69.09	2.46	-0.13	2.59	0.0066	0.072	0.0058	11.7
32-9	22	38	5762.82	8	86.74	2.72	-0.23	2.95	0.0066	0.092	0.0053	15.2
32-8	23	38	5762.82	11	107.48	2.84	-0.33	3.16	0.0066	0.102	0.0048	17.1
32-7	***24***	***38***	***5762.82***	***14***	***134.38***	***2.86***	***-0.44***	***3.30***	***0.0066***	***0.104***	***0.0043***	***17.5***
32-6	25	38	5762.82	15	170.47	2.67	-0.48	3.15	0.0066	0.088	0.0041	14.4
32-5	26	38	5762.82	17	219.71	2.53	-0.56	3.09	0.0066	0.077	0.0038	12.6
32-4	27	38	5762.82	19	292.39	2.34	-0.65	2.99	0.0066	0.065	0.0035	10.4
32-3	28	38	5762.82	21	399.12	2.12	-0.74	2.86	0.0066	0.053	0.0031	8.3
32-2	29	38	5762.82	25	590.5	1.89	-0.97	2.86	0.0066	0.042	0.0025	6.6

Table 2. *Weights of Evidence results for vein density and Tiers (1 plus 2) tungsten occurrences (occ. = occurrences, prob. =probability). Italicized and emboldened values correspond to the maximum values of W+ and Wdiff in Figure 6. See text for explanation.*

by the method, and the area that could be explored with the funds available.

In this illustrative example, W+ and Wdiff reach a maximum at the same density category, 24, corresponding to an 'in' area of 134.38 km^2 illustrated in Figure 6. Within these areas, the posterior probability of a square kilometre being mineralised is 0.104 or about one in ten (post prob. 'in' of Table 2) and the chance of the area being mineralised is 17.5 times it was before consideration of the distribution of known occurrences in relation to mapped veins (exp(W+)) of Table 2).

Figure 7 is the equivalent of Figure 6 with (Tier 1 plus 2) occurrences corrected so that there is no more than one occurrence in each square kilometre. Comparison of these figures highlights the differences between them which fall mainly at low density categories. They are caused by the fact that, after correction (Figure 7), a few occurrences fall inside the 'in' area at anomalously low density categories producing the saw-tooth at these density categories. A similar effect is noticed with other exploration datasets (a full set of results as Excel spreadsheets is available on request). Nevertheless, the maximum values of W+ and Wdiff fall at almost exactly the same density category (23 compared to 24) and identify almost exactly the same 'in' areas although, because fewer tungsten occurrences are considered (31 as opposed to 38), the maximum values of these measures are somewhat less (2.70 compared with 2.86 for W+ and 2.98 compared with 3.30 for Wdiff). Figure 8 illustrates the mapped output of the program using vein density and corrected Tier (1 plus 2) mineral occurrences.

Figure 9 illustrates the combinations of different selections of tungsten occurrences with different exploration data that were investigated during the study. Tests were carried out on the most important occurrences (Tier 1), on Tiers (1 & 2) and the same selection corrected for occurrences that fall within the same square kilometre as discussed above. Tests were also carried out using all the tungsten occurrences of Table 1 and those where the mineralisation occurs as a vein complex rather than as individual lodes. The purpose of the comparisons was to find out if the method identifies differences in the controls on mineralisation, depending on the selection of different categories of occurrence. Clearly, if a different set of controls, expressed by the exploration data, is indicated for the major occurrences, or for vein complexes that might lend themselves to open cast exploitation, then this would be a valuable finding of the work. Similarly, if the inclusion of all the occurrences led to a significantly improved outcome over Tiers (1 & 2), then there would be merit in expending more effort in identifying further occurrences of tungsten mineralisation reported in the literature.

The outcomes of the method for a selection of these combinations are set out in Figure 10. The selections illustrated are based exclusively on Tiers (1 plus 2) mineral occurrences corrected so that no more than one occurrence falls in each square kilometre (see conclusions and discussion below). Results using mapped geological units have been excluded since they mimic those for proximity to the granite contact but with less discrimination. Two approaches were used with the gravity data. The program was run assigning all the outcropping granites to the lowest slope class on the basis that they are in effect 'highs' in the granite envelope surface. The

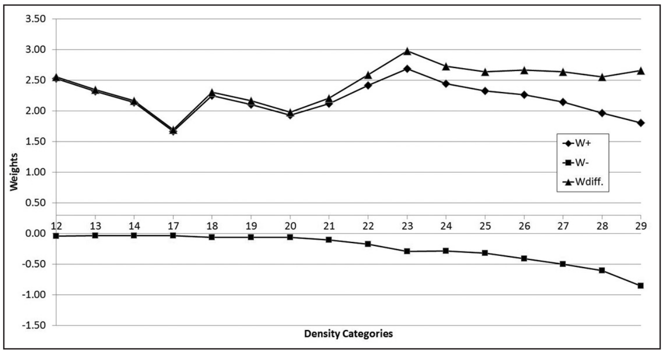

Figure 7. *Weights of Evidence for the vein density categories of Table 3.*

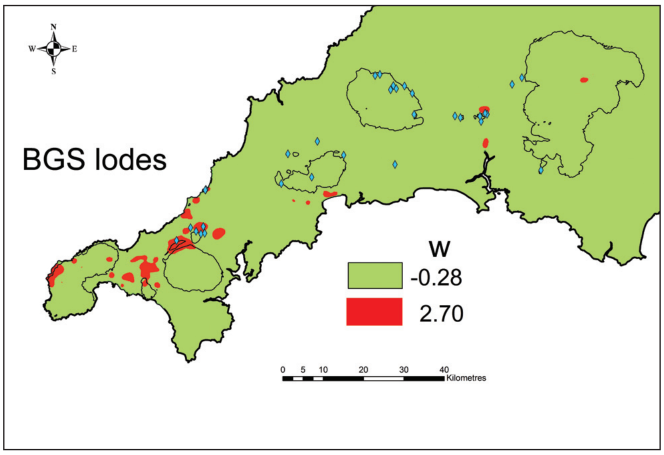

Figure 8. *Weights of Evidence outcome for BGS veins and corrected Tier (1 plus 2) tungsten occurrences. Black outline = granite margin, blue diamonds = corrected Tier (1 plus 2) tungsten occurrences.*

Density classes	Density categories	Total occ.	Total area (km^2)	Occ. 'in'	Area 'in'	W+	W-	Wdiff.	Prior prob.	Post prob. 'in'	Post prob. 'out'	Exp(W+)
32-19	12	31	5762.82	1	15.72	2.53	-0.04	2.56	0.0054	0.0636	0.0052	12.6
32-18	13	31	5762.82	1	19.10	2.32	-0.03	2.35	0.0054	0.0523	0.0052	10.2
32-17	14	31	5762.82	1	22.61	2.14	-0.03	2.17	0.0054	0.0442	0.0052	8.5
32-14	17	31	5762.82	1	35.62	1.67	-0.03	1.70	0.0054	0.0280	0.0052	5.3
32-13	18	31	5762.82	2	40.67	2.25	-0.06	2.31	0.0054	0.0491	0.0051	9.5
32-12	19	31	5762.82	2	46.77	2.11	-0.06	2.17	0.0054	0.0428	0.0051	8.2
32-11	20	31	5762.82	2	55.62	1.93	-0.06	1.98	0.0054	0.0360	0.0051	6.9
32-10	21	31	5762.82	3	69.09	2.12	-0.10	2.21	0.0054	0.0434	0.0049	8.3
32-9	22	31	5762.82	5	86.74	2.42	-0.17	2.59	0.0054	0.0576	0.0046	11.2
32-8	***23***	***31***	***5762.82***	***8***	***107.48***	***2.70***	***-0.29***	***2.98***	***0.0054***	***0.0744***	***0.0041***	***14.7***
32-7	24	31	5762.82	8	134.38	2.45	-0.28	2.73	0.0054	0.0595	0.0041	11.6
32-6	25	31	5762.82	9	170.47	2.33	-0.32	2.64	0.0054	0.0530	0.0039	10.3
32-5	26	31	5762.82	11	219.71	2.27	-0.41	2.67	0.0054	0.0500	0.0036	9.7
32-4	27	31	5762.82	13	292.39	2.15	-0.50	2.64	0.0054	0.0444	0.0033	8.6
32-3	28	31	5762.82	15	399.12	1.97	-0.60	2.56	0.0054	0.0376	0.0030	7.2
32-2	29	32	5762.82	19	590.50	1.81	-0.85	2.66	0.0054	0.0322	0.0023	6.1

Table 3. *Weights of Evidence results for vein density and Tier (1 plus 2) tungsten occurrences corrected so that only one occurrence falls in each square kilometre (occ. = occurrences, prob. =probability). Italicized and emboldened values correspond to the maximum values of W+ and Wdiff in Figure 7. See text for explanation.*

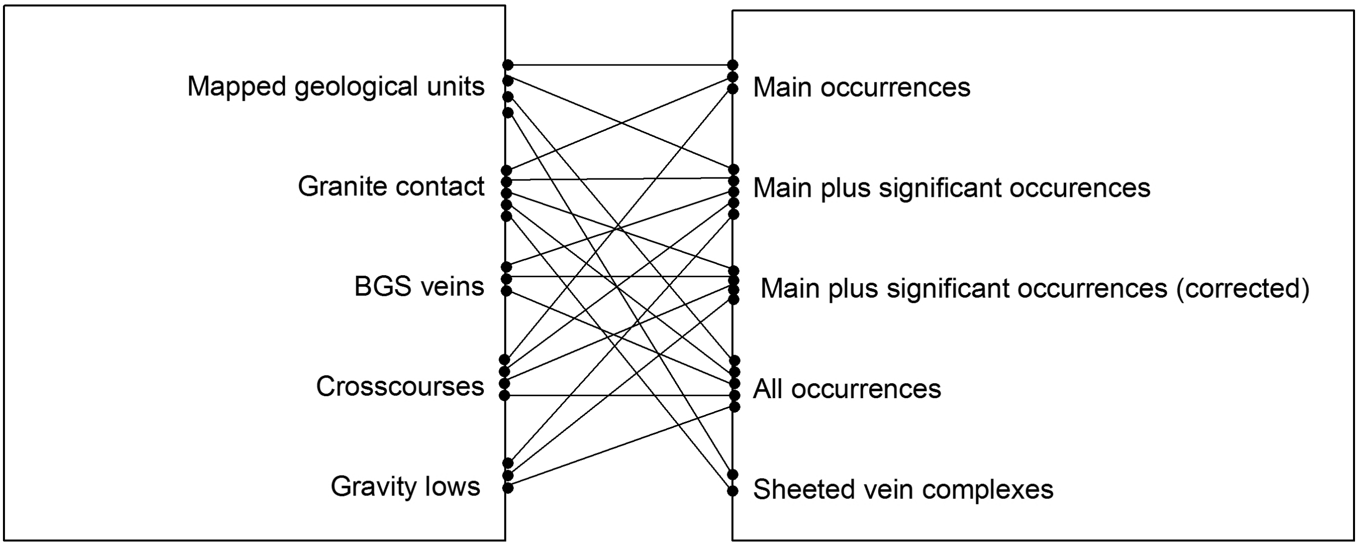

Figure 9. *Combinations of exploration data and tungsten occurrences used in the study.*

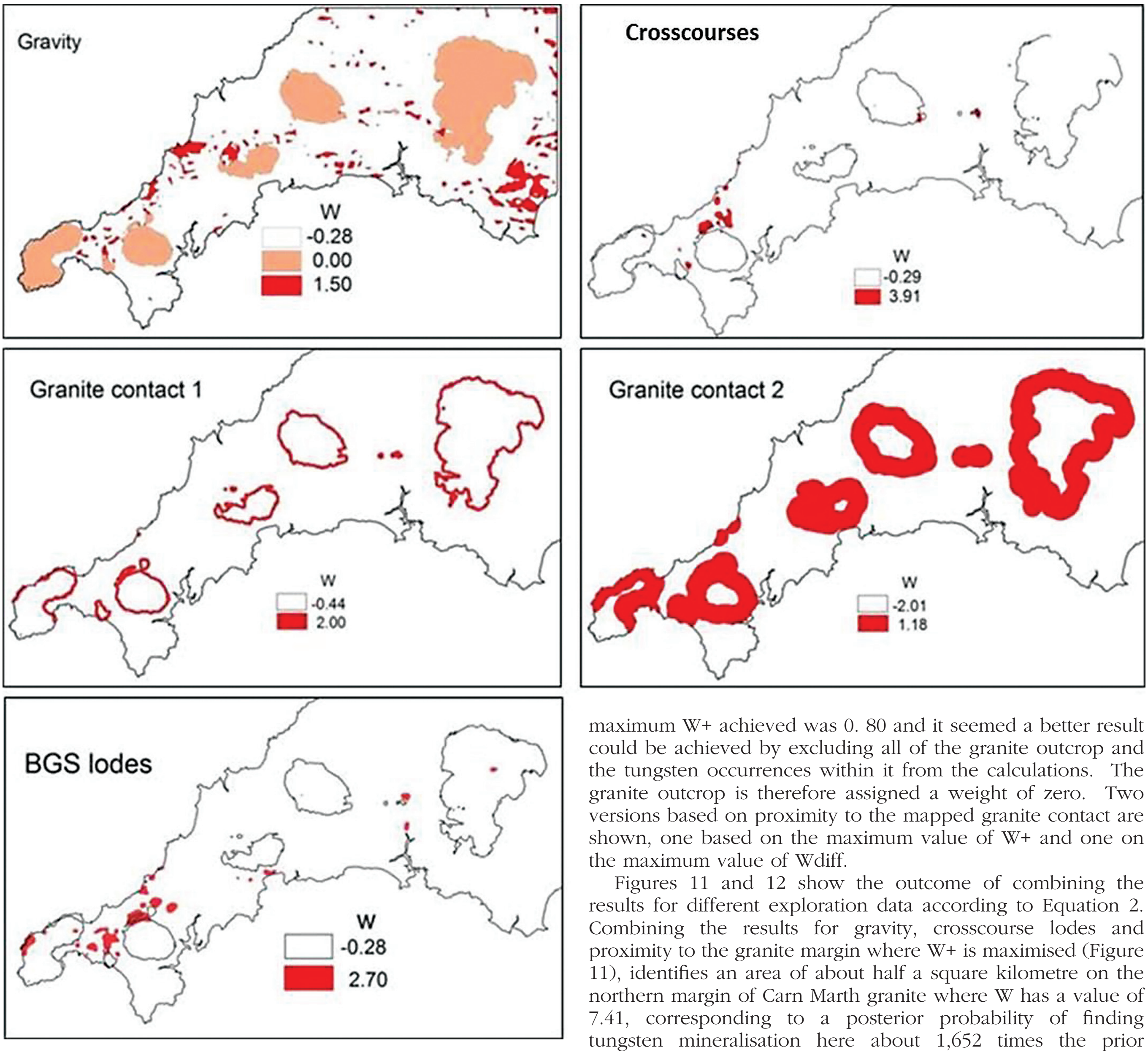

Figure 10. *Mapped weights for corrected Tier (1 plus 2) tungsten occurrences and different exploration data.*

maximum W+ achieved was 0. 80 and it seemed a better result could be achieved by excluding all of the granite outcrop and the tungsten occurrences within it from the calculations. The granite outcrop is therefore assigned a weight of zero. Two versions based on proximity to the mapped granite contact are shown, one based on the maximum value of W+ and one on the maximum value of Wdiff.

Figures 11 and 12 show the outcome of combining the results for different exploration data according to Equation 2. Combining the results for gravity, crosscourse lodes and proximity to the granite margin where W+ is maximised (Figure 11), identifies an area of about half a square kilometre on the northern margin of Carn Marth granite where W has a value of 7.41, corresponding to a posterior probability of finding tungsten mineralisation here about 1,652 times the prior probability. This very small area falls within a zone of about 20 km^2 located in a discontinuous band extending from the east

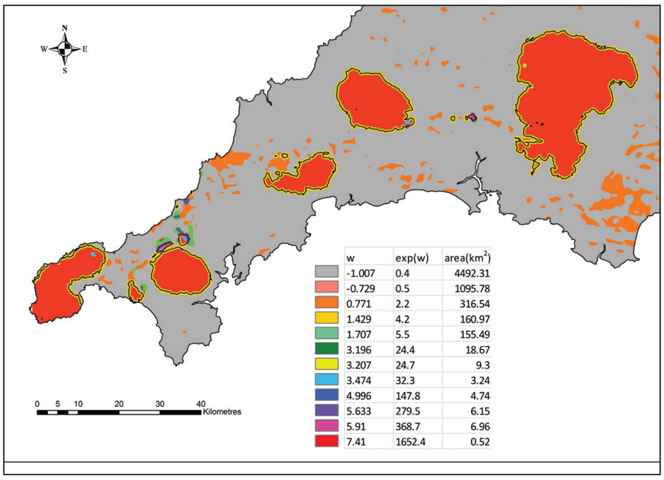

Figure 11. *Tungsten prospectivity map based on combining proximity to the granite margin where W+ is maximised, crosscourses and gravity anomalies.*

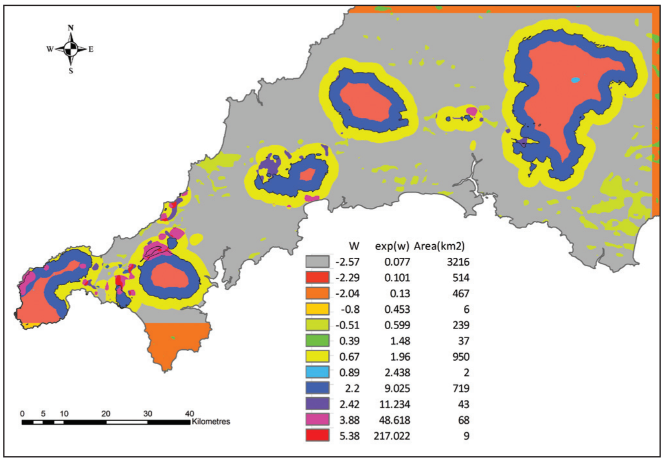

Figure 12. *Tungsten prospectivity map based on combining proximity to the granite margin where Wdiff is maximised, BGS lodes and gravity anomalies.*

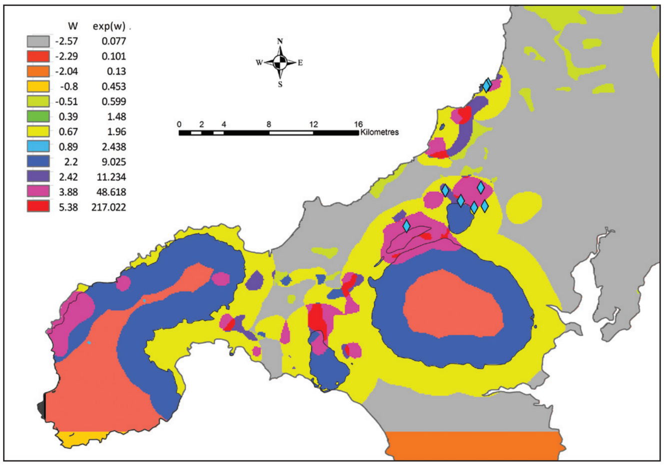

Figure 13. *Detail of southwest part of Figure 12. Blue diamonds = tungsten occurrences of Tier (1 plus 2) corrected so that no more than one falls in each square kilometre.*

side of the Godolphin Granite in the south, through the eastern margins of the Carn Marth Granite to St Agnes and Cligga Head with outliers at the southeast extremity of the Bodmin Moor Granite and at Gunnislake, where the calculated probability of finding tungsten mineralisation is in excess of 145 times this probability before considering the exploration data. Within this zone, the posterior probability of finding a square kilometre of ground with tungsten mineralisation similar to that represented by Tier 1 and Tier 2 occurrences approaches or exceeds one; the method indicates that the chances of encountering this kind of mineralisation in these localities is very good indeed.

Figure 12 illustrates the outcome produced by combining the weights maps for gravity, the density of lodes shown on the BGS mapping and proximity to the granite margins where Wdiff is at a maximum. The map indicates a zone of generally elevated tungsten prospectivity extending from the northern part of the Godolphin Granite, through Carn Brea and Carn Marth to St Agnes and Cligga Head with outliers on the west coast of the Land's End Granite, around St Austell and northeast of Kit Hill. The maximum weight covers an area of about 9 km^2 located within the main zone of high values (Figure 13). Its value of 5.38 corresponds to a probability of finding tungsten mineralisation about 217 times the probability before taking the exploration data into account.

Discussion and conclusions

Application of the maximum weights in Figures 11 and 12 to the prior probability of tungsten mineralisation produces posterior probabilities in excess of one, an impossible outcome. There are several possible reasons for this. The most important is probably the lack of statistical independence mentioned previously, between the known tungsten occurrences and the mapped location of lodes and veins. It is inevitable that both will be plentiful where exploration has been most intense; this produces a false correlation between these two sets of distributions which distorts the outcome of the method. A further disadvantageous consequence is that the zones highlighted by the method tend to be those where known mineral occurrences are most widespread. The actual weight values should therefore be treated with considerable caution although the relative values and the location of the more prospective areas may have more validity.

It has been suggested, *particularly in the case of sheeted vein complexes*, that there is an association of tungsten mineralisation with porphyritic textures in the enclosing granite. While this might seem to be a promising additional control on the mineralisation, its application is problematic since there is no map of porphyry textures in the granites that is independent of known mineralisation or can make a claim to be uniform across the whole area. Similarly, the Hemerdon and Cligga Head sheeted vein complexes are now known to be associated with north-south structures related to crosscourses, in the latter case resulting in the north-south elongation of the exposed granite body. However, because this control was not widely known *a priori* at these localities and does not appear in the mapped exploration data used for the study, it has not been taken into account in calculating the weights.

The results using Tiers (1 & 2), corrected and uncorrected, have been shown to be broadly similar. The outcomes of the method using only the largest tungsten occurrences (Tier 1) appear, on the basis of a small number of runs, also to be similar. For example, the maximum value of Wdiff for crosscourses and the four Tier 1 occurrences selected is 3.9 at density classes in the range 32-9 inclusive, covering an area of 107 km^2, while the corresponding measures for corrected Tier (1 & 2) occurrences are 3.84, 32-15 and 33 km^2 respectively, corresponding to a much more tightly constrained prospective area. On this limited basis, it is concluded that the controls of major occurrences of tungsten do not differ significantly from other occurrences. While the results assign reasonable levels of prospectivity to East Pool and Agar, Cligga Head and Castle-an-

Dinas occurrences, they fail to highlight Hemerdon which is not associated with any of the mapped exploration data except proximity to a granite contact. There is uncertainty in correct interpretation of outcomes based on Tier 1 locations of which there are only four. More work might indicate some differences in the control on the location of major occurrences but has not so far been attempted.

The results using Tiers (1 & 2 & 3) produce lower values of W+ and Wdiff than the results using Tiers (1 & 2); it is concluded that where minor occurrences of tungsten are included, the indicated pattern of mineralisation is more diffuse than that based on more significant ones; it may well be that wolfram occurs in small quantities almost everywhere in and around the granites where there are veins, including zones where the latter have not been mapped. If this is the case, then any attempt to include all known occurrences in future work would be counter-productive. In this respect, it is of interest that the northeast margin of the Bodmin Moor Granite contains seven significant tungsten occurrences but lacks mapped veins or lodes. Once more, there is a question mark over the completeness and uniformity of the exploration data used which detracts from the confidence that can be placed in the outcome.

There is a question mark over independence among the exploration datasets, which also throws doubt on the outcome. While this statistical independence has not been tested, in common with most other occasions where the method has been applied, the data would probably fail the test (Agterberg and Cheng, 2002). This is another reason to view the results with caution. The results for sheeted vein complexes though limited in scope, show rather different results from those based on BGS veins or crosscourses and there may be merit in further investigation because of their potential importance as a source of tungsten won by open cast.

The results indicate that the granite aureoles are more prospective than either the granites themselves of combinations of granite and aureole rocks but these criteria are less effective than proximity to the granite contact. All the tests were carried out with proximity zones symmetrical about the granite contacts; inspection of the data suggests that improved results could be achieved with asymmetric zones, wider in the aureole rocks and narrower in the granites.

The results of the work may be summarised as follows:

1) 'Best' areas based on all tungsten occurrences are less well defined and have proportionately lower maximum W+ and Wdiff values than the result using main plus significant occurrences.

2) The results based on four main occurrences are not significantly different from those based on main plus significant occurrences.

3) Based on limited investigation, the controls on mineralised tungsten vein complexes appear to differ from the controls on tungsten mineralisation in lodes; further investigation is merited.

4) Correcting for mineralised areas rather than mineral occurrences reduces W+ but has minimal effect on the corresponding areas assigned W+ and W- values.

5) The method concentrates the mind on the relevance and completeness of exploration data. It permits an objective evaluation of individual exploration criteria in the light of known mineral occurrences which is perhaps its main benefit.

6) Inconsistent and/or incomplete mapping of exploration data, lack of independence within the exploration data and between these data and the mineral occurrences detract from the statistical rigour of the method and require the results to be viewed with caution.

7) In terms of power of discrimination, mapped crosscourses are the most effective exploration criterion producing the smallest prospective areas with the highest value of W+.

8) A discontinuous zone of enhanced tungsten prospectivity is outlined by combining individual prospectivity maps. It extends from the Godolphin Granite through the Carn Brea and Carn Marth Granites to St Agnes and Cligga Head. The high prospectivity zone is made up partly by areas close to and within the granite outcrop, joined together by areas where the gravity field indicates that granite cupolas are present in the near subsurface. There is general agreement on the location and extent of this zone in the two exploration data combinations illustrated. Further prospective zones where the combinations disagree are located on the west side of the Land's End Granite, southeast margin of the Bodmin Moor Granite, at and to the north of Gunnislake and near the south margin of the St Austell Granite, east of the town of St Austell and on the northwest margin of the St Austell Granite around Castle an Dinas.

9) None of the approaches using different categories of tungsten occurrence highlighted Hemerdon as a particularly prospective locality.

10) In spite of the shortcomings identified, the method has a significant part to play for tungsten exploration in the southwest peninsula by helping to identify areas of a size matched to existing exploration budgets with increased chances of encountering further tungsten mineralisation.

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