

Porphyry Copper Deposit Tract Definition – A Global Analysis Comparing Geologic Map Scales

Gary L. Raines,^{1,4} Katherine A. Connors,² and Lesley B. Chorlton³

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Geologic maps are a fundamental data source used to define mineral-resource potential tracts for the first step of a mineral resource assessment. Further, it is generally believed that the scale of the geologic map is a critical consideration. Previously published research has demonstrated that the U.S. Geological Survey porphyry tracts identified for the United States, which are based on 1:500,000-scale geology and larger scale data and published at 1:1,000,000 scale, can be approximated using a more generalized 1:2,500,000-scale geologic map. Comparison of the USGS porphyry tracts for the United States with weights-of-evidence models made using a 1:10,000,000-scale geologic map, which was made for petroleum applications, and a 1:35,000,000-scale geologic map, which was created as context for the distribution of porphyry deposits, demonstrates that, again, the USGS US porphyry tracts identified are similar to tracts defined on features from these small scale maps. In fact, the results using the 1:35,000,000-scale map show a slightly higher correlation with the USGS US tract definition, probably because the conceptual context for this small-scale map is more appropriate for porphyry tract definition than either of the other maps. This finding demonstrates that geologic maps are conceptual maps. The map information shown in each map is selected and generalized for the map to display the concepts deemed important for the map maker's purpose. Some geologic maps of small scale prove to be useful for regional mineral-resource tract definition, despite the decrease in spatial accuracy with decreasing scale. The utility of a particular geologic map for a particular application is critically dependent on the alignment of the intention of the map maker with the application.

KEY WORDS: Map scale, weights-of-evidence, porphyry deposits of world.

INTRODUCTION

It is generally believed that the scale of the data to be used is a critical consideration in an analysis. Levin (1992) argues that scale of observation is a filter for processes. At different scales of observation, different processes are observed. This hypothesis is particularly well supported when measured data, such as geophysical measurements, are used as

the primary predictor. Nykanen and Raines (2007) used aeromagnetic data from Finland with a line spacing of 200 m for an analysis of scale in predicting the long, thin gold deposits in a greenstone belt. By selecting increasingly wider line spacing, they demonstrated that the correlation with the deposits decreased in a manner consistent with conventional wisdom of the properties of scale. Thus, as the line spacing increased (resulting in a smaller map scale), the correlation with the gold deposits decreased. In another study, Raines and Mihalasky (2002) used the 1:2,500,000-scale King and Beikman geology of the United States (King and Beikman, 1974) to predict the location of porphyry deposits, and found a good correlation with resource tracts defined by the 1:1,000,000-scale USGS porphyry assessment of

¹U.S. Geological Survey, c/o Mackay School of Earth Sciences, UNR, Reno, NV, 89557, USA.

²Geologic Data Systems, Denver, CO, USA.

³Geological Survey of Canada, Ottawa, ON, Canada.

⁴To whom correspondence should be addressed; e-mail: graines@usgs.gov

the United States (U.S. Geological Survey National Mineral Assessment Team, 1998). It should be pointed out that King and Beikman made a point to differentiate felsic magmatic domains, which are believed to be associated spatially with the felsic porphyry intrusions that typically host porphyry copper deposits. The USGS assessment was based on 1:500,000-scale geology of the individual states and other larger scale information and was published for use at a scale of 1:1,000,000.

The differing results of these two studies indicate that the utility of the scale of map information cannot be separated easily from differences in map information content portrayed at different scales. For geologic map, only an insignificant decrease in correlation with the USGS US porphyry tracts occurs with a large decrease in map scale; whereas, for a decrease in scale for geophysical measurements, correlation decreases with each decrease in scale. This poses the question: what is different about geologic maps that lead to the apparent contradiction in the properties of scale? The answer seems to be that geologic maps are illustrations of geologic relationships rather than simple, scale-dependent measurements. Depending on the type of geologic map, small-scale maps may be effective in capturing the important information elements for a specific analysis, despite the expected inadequacy of scale. This is not to imply that such map could replace the large-scale maps that are clearly required to address more focused and spatially rigorous problems such as where to drill the next exploration hole. In fact, it should be noted that maps of the scales discussed here (1:1,000,000 and smaller) generally are compilations from larger scale maps. Whatever the intent of the compiler, the resultant map is dependant on the high-quality observations recorded at the larger scale so that the pertinent geologic relationships can be preserved at the smaller scale, despite the reduction in spatial accuracy. Clearly, large-scale maps are essential for some tasks; however, the objectives of a national or even global assessment of a mineral resource include defining the regional extent and locations where the resource is likely to occur. For this application, small-scale maps may prove surprisingly effective.

In this analysis, two global geologic maps prepared for different purposes at differing scales were used to evaluate the interplay between map scale and information content in spatial analysis. The geologic maps at 1:10,000,000- and 1:35,000,000-scale were used as predictors of porphyry deposits.

The Mutschler, Ludington, and Bookstorm (1999) compilation of global giant copper camps is used as training points for simple weights-of-evidence (WofE) models based on a single evidence layer, a multiclass generalization of the geologic map. The global assessment tracts derived from these two maps using similar WofE techniques are compared in this report to the USGS porphyry tracts of the US to evaluate the spatial modeling effects of differing scales and information content.

The WofE method used in this study (Bonham-Carter, 1994) is an objective data-driven analysis technique that can be used to compare the prediction utility of differing spatial data sets. In this example, two different sets of geologic map units, compiled at different scales, will be used to predict porphyry copper deposit locations. By considering the confidence measures of the contrast from the WofE method, the geologic map units can be generalized into multiple, statistically significance classes as discussed in Raines and Bonham-Carter (2006). This approach creates a multiclass posterior probability map of the spatial occurrence of the training points. This multiclass posterior probability map then can be compared to the previously defined USGS porphyry copper tracts of the United States (USGS National Assessment Team, 1998) to measure the prediction utility of the differing geologic maps compiled at different scales. For the analysis conducted here, the two geologic map compilations were the Exxon Tectonic Map of the World, which is referred to as the *Tectonic map* in this report and has a map scale of 1:10,000,000 and the Geological Survey of Canada Felsic/Intermediate Igneous Rock Map, which is referred to as the *F/I Igneous map* in this report and has a map scale of 1:35,000,000 scale. As evident in the descriptions of the maps and their sources below, these maps were generated not only at different scales, but were generated using vastly different conceptual principles. The Tectonic Map focused on representing the distribution of the world's sedimentary basins, whereas the F/I Igneous map was generated to illustrate the distribution of porphyry-related igneous rocks. Thus, the map's scale and conceptual framework are confounded in this WofE analysis.

Exxon Tectonic Map (1:10,000,000-scale Tectonic Map)

The Exxon Tectonic Map of the World was compiled in 1985 by the World Mapping Project as a

cooperative effort with Exxon affiliates to show the tectonic setting of the world's sedimentary basins and its oil and gas deposits. Sources of information included published and unpublished maps and reports of Exxon affiliates, as well as public domain data. The project was carried out under the principal direction of J. M. Widmier (Basin Exploration Division), A. R. Creen (Basin Systems Section) and K. T. Biddle (Basin Analysis Section). In 1994, Exxon Production Research Company donated the Tectonic Map of the World to the American Association of Petroleum Geologists Foundation and the map was made publicly available. In 1995, the 1:10,000,000 scale maps were provided to Geologic Data Systems for digital conversion, where the maps were enlarged and digitally compiled at a scale of 1:5,000,000. Polygon, line, and point attribute information was captured for use in a GIS environment, bathymetric contours were updated using the current GEBCO (General Bathymetric Chart of the Ocean) data, and index hypsographic contours were added from the DCW (Digital Chart of the World). The data used in this study were provided by Geologic Data Systems, who hold exclusive rights for the distribution of the digital Tectonic Map of the World.

Felsic/Intermediate Igneous Rock Map (1:35,000,000-scale)

The 1:35,000,000-scale Felsic/Intermediate Igneous Rock Map (F/I Igneous map) prepared at the Geological Survey of Canada and used in this investigation depicts the generalized global distribution of felsic and intermediate intrusive and volcanic rocks, subdivided by age at the era level, against a backdrop of unclassified Precambrian and Phanerozoic age domains (Chorlton, 2004a). The map is the result of an effort to identify magmatic tracts potentially related to porphyry deposits and is a secondary thematic data set derived from the Generalized Geology of the World (GGW) GIS data set and linked rock unit attribute database (Chorlton, 2004b). This data set contains bedrock unit information from geological compilation maps of between 1: 2,000,000 and 1:5,000,000 paper scales, supplemented by other regional thematic map and literature sources. Its attribute database was designed to accommodate the most significant parameters for each geological domain, which include start and end ages, lithologic components in three levels

of detail, stratigraphic or lithologic unit and geological province names, and tectonic settings. Emphasis was placed primarily on populating the age ranges and highest levels of lithologic detail, and secondarily on capturing information related to magmatic composition to compliment databases of magma-related mineral deposits (Chorlton, Sinclair, and Laramée, 2002).

The spatial components of the GGW are known to be imprecise. The accuracy of many paper map sources was poor, and intricate spatial detail in source data sets considered relatively accurate was generalized for consistency. To hide small spatial features or clusters of features for most uses, but retain them in easy-to-visualize form for special purposes, advantage was taken of the ability to store more than one record set (unit) per GIS feature. The small features or clusters were represented as single exaggerated polygons, and a default record set representing the enclosing geological domain was appended to the database. One or more extra record sets then were added so that the same feature could be retrieved when the database is queried for the special interest component. These exaggerated small features, therefore will be spatially over-represented in the map, an effect that occurs in manually prepared thematic compilations where exaggeration has been applied.

To create the digital map of the global distribution of felsic or intermediate intrusive and volcanic rocks subdivided by age, new attribute fields were appended to copies of the GGW vector data (polygon coverages) and then populated with values based on the results of sequential database queries to create a flat file data set. All possible record sets were included in these queries, not just defaults. For domains containing both intrusive and extrusive magmatic components of the appropriate composition, extrusive components took precedence in the output because of the order in which queries were applied. Arcs separating identically classified polygons were dropped to create the final, simplified output, the purpose of which was to provide visual context for the world distribution of major intermediate-felsic magma-related deposits, principally porphyry copper deposits.

MODEL DEFINITIONS

The intent of the modeling reported here was to use the geologic maps to make simple multiclass

Table 1. Generalization of the Tectonic map with Regards to Porphyry Deposits

Generalization class	Convergent margin	Age	Rock class	Rock subclass	Contrast	STD	Studentized contrast
Inside Class 19	True	Miocene to Recent	Igneous	Intrusive	3.8901	0.5805	6.7015
Inside Class 18	True	U. Cretaceous (Santonian)-Oligocene	Igneous	Intrusive	3.7848	1.0018	3.778
Inside Class 17	True	U. Cretaceous (Santonian)-Oligocene	Igneous	Intrusive	2.8342	0.232	12.2137
Inside Class 16	True	Middle Triassic to Middle Jurassic	Igneous	Extrusive	2.809	0.3388	8.2905
Inside Class 15	False	Precambrian (2.0–3.0 b.y.)	Igneous and Metamorphic		2.5538	1.0018	2.5492
Inside Class 14	True	U. Cretaceous (Santonian)-Oligocene	Igneous	Extrusive	2.2477	0.284	7.9137
Inside Class 13	True	Middle Triassic to Middle Jurassic	Igneous	Intrusive	2.0535	0.4127	4.9759
Inside Class 12	True	Miocene to Recent	Igneous	Extrusive	2.0447	0.2437	8.3914
Inside Class 11	True	U. Cretaceous (Santonian)-Oligocene	Igneous		1.9987	0.1853	10.7836
Inside Class 10	True	U. Precambrian(800 my) – M. Cambrian	Igneous	Extrusive	1.9217	1.0018	1.9182
Inside Class 9	False	Precambrian (1.85–1.7 b.y.)	Igneous and Metamorphic		1.7105	1.0018	1.7074
Inside Class 8	False	Pennsylvanian to Lower Triassic	Igneous	Extrusive	1.6954	0.7096	2.3891
Inside Class 7	False	Precambrian (1.0 b.y.)	Igneous and Metamorphic		1.6857	1.0018	1.6827
Inside Class 6	True	Middle Devonian to Mississippian	Igneous	Extrusive	1.5733	1.0018	1.5705
Inside Class 5	True	U. Jurassic-U. Cretaceous (Coniacian)	Igneous	Intrusive	1.3908	0.322	4.3189
Inside Class 2	True	Upper Cambrian to Lower Devonian	Igneous	Extrusive	1.1415	1.0018	1.1394
Inside Class 4	True	Pennsylvanian to Lower Triassic	Igneous	Intrusive	0.8969	0.4513	1.9875
Inside Class 3	False	Miocene to Recent	Igneous	Extrusive	0.8516	0.3828	2.2247
Inside Class 1	False	Middle Devonian to Mississippian	Igneous	Intrusive	0.6722	1.0018	0.671
Inside Class 2	False	Miocene to Recent	Igneous		0.6579	0.4127	1.5942
Inside Class 1	True	U. Jurassic-U. Cretaceous (Coniacian)	Igneous	Extrusive	0.3366	0.5036	0.6683
Inside Class 1	False	U. Precambrian (800 my) – M. Cambrian			0.2634	0.3828	0.6882
Inside Class 1	False	Middle Triassic to Middle Jurassic			0.17	0.5805	0.2928
Inside Class 1	False	Precambrian (>2.5 b.y.)	Igneous and Metamorphic		0.1678	1.0018	0.1675
Inside Class 1	False	Precambrian (2.5–2.8 b.y.)	Igneous and Metamorphic		0.1333	1.0018	0.133
Inside Class 1	False	Middle Devonian to Mississippian			0.1133	0.3388	0.3345

The classes are sorted by contrast. The convergent-margin igneous rocks, except for those highlighted in bold, are treated as individual classes with at least 85% confidence, which is the reported confidence is not zero. Those map units highlighted in bold are treated as one class because individually they had low confidence. Combined their confidence is 1.1, which is about 85% confidence. A studentized contrast of 1.28 is about 90%; so all the others are greater than 90% confidence. Known porphyry copper deposits did not occur in all other map units not shown in the Table.

Table 2. Generalization of the F/I Igneous Map with Regards to Porphyry Deposits

Class	Map Unit	Contrast	STD	Studentized Contrast
Inside 11	Paleozoic-Mesozoic felsic and/or intermediate intrusive domains	3.111	0.5805	5.3595
Inside 10	Cenozoic felsic and/or intermediate intrusive domains	2.8092	0.3587	7.8318
Inside 9	Mesozoic felsic and/or intermediate intrusive domains	2.1198	0.2221	9.5456
Inside 8	Cenozoic felsic and/or intermediate volcanic domains	1.8995	0.2134	8.8993
Inside 7	Paleozoic felsic and/or intermediate volcanic domains	1.7606	0.4127	4.2663
Inside 6	Precambrian-Paleozoic felsic and/or intermediate intrusive domains	1.6111	1.0018	1.6083
Inside 5	Mesozoic-Cenozoic felsic and/or intermediate intrusive domains	0.9466	0.3828	2.473
Inside 4	Precambrian felsic and/or intermediate volcanic domains	0.8761	0.7096	1.2346
Inside 3	Precambrian felsic and/or intermediate intrusive domains	0.3519	0.2221	1.5846
Inside 2	Precambrian-Phanerozoic unclassified domains	0.0249	0.5036	0.0495
Inside 2	Mesozoic felsic and/or intermediate volcanic domains	0.394	0.5805	0.6787

The classes are sorted by contrast. The bottom two map units, highlighted in bold, are generalized into one class to achieve a confidence of slightly greater of 60%. All of the other classes have approximately 90% or greater confidence that the contrast is not zero. All other map units, not shown, had no association with porphyry deposits.

predictive models of the distribution of porphyry deposits. All calculations were done in ArcSMD (Kemp and others, 2001). The 283 training points used are “significant” copper camps of the globe that are defined in Mutschler, Ludington, and Bookstrom (1999). No attempt has been made in these simple models to differentiate porphyry deposits by type. Of the 283 training points, 221 were classified as porphyry deposits, and most of the others are of types usually associated with porphyry deposits. A WofE model (Bonham-Carter, 1994) provides a measure of correlation with the training points, designated as the *contrast*, and a measure of the confidence in the contrast, designated as the *Studentized contrast* (contrast divided by its standard deviation). This confidence measure is a test that the reported contrast is not equal to zero. Map units having a significant contrast are summarized in Tables 1 and 2. Each of these listed map units were used in the model and assigned a distinct weight in the conventional weights analysis in the WofE model (Raines and Bonham-Carter, 2006). For the Tectonic Map, a confidence level of approximately 85% was considered significant. For the F/I Igneous Map, most of the units attained a confidence level of 85% except for two igneous rock domains that individually had a weak association with a low confidence level. By combining these two map units, an association with approximately 60% confidence was attained. All other map units in both maps are generalized into one class that is not associated with copper camps. For this global analysis these minimum levels of confidence were arbitrarily considered sufficient in the context that the final response themes will be grouped into two classes for comparison to the US assessment, and thus other

groupings with higher levels of confidence were not investigated. Examples from the resulting models are shown in Figure 1.

COMPARISON OF MODELS

In order to evaluate these models by comparison with the USGS porphyry tracts of the United States (Fig. 1C), it is necessary to reduce the multi-classes to binary, permissive and nonpermissive, classes as used for the USGS porphyry tracts. This generalization of the global models consists of everything with colors warmer than blue in Figure 1, where the prior probability (Bonham-Carter, 1994) is used to define the break between permissive versus nonpermissive areas. There are several ways to compare the Tectonic and F/I Igneous models with the USGS tracts. The maps can be compared directly, as shown in Table 3, where it can be seen that the Tectonic map slightly underestimated the permissive areas in relation to the USGS tracts. The F/I Igneous map slightly underestimated the permissive areas. The agreement between the Tectonic map model and the USGS tracts is slightly less than that reported by the Raines and Mihalasky (2002) for the model derived from the King and Beikman 1:2,500,000-scale geologic map. Whereas, the agreement between the F/I Igneous and USGS tracts is slightly better than reported by Raines and Mihalasky (2002). This increase in agreement with decreasing scale also is reflected in Jaccard’s Similarity Coefficient (shown as Jaccard’s C in Table 3). Jaccard’s Similarity Coefficient disregards the match of the nonpermissive areas, so it is less influenced by the rarity of training sites that inflates the agreement

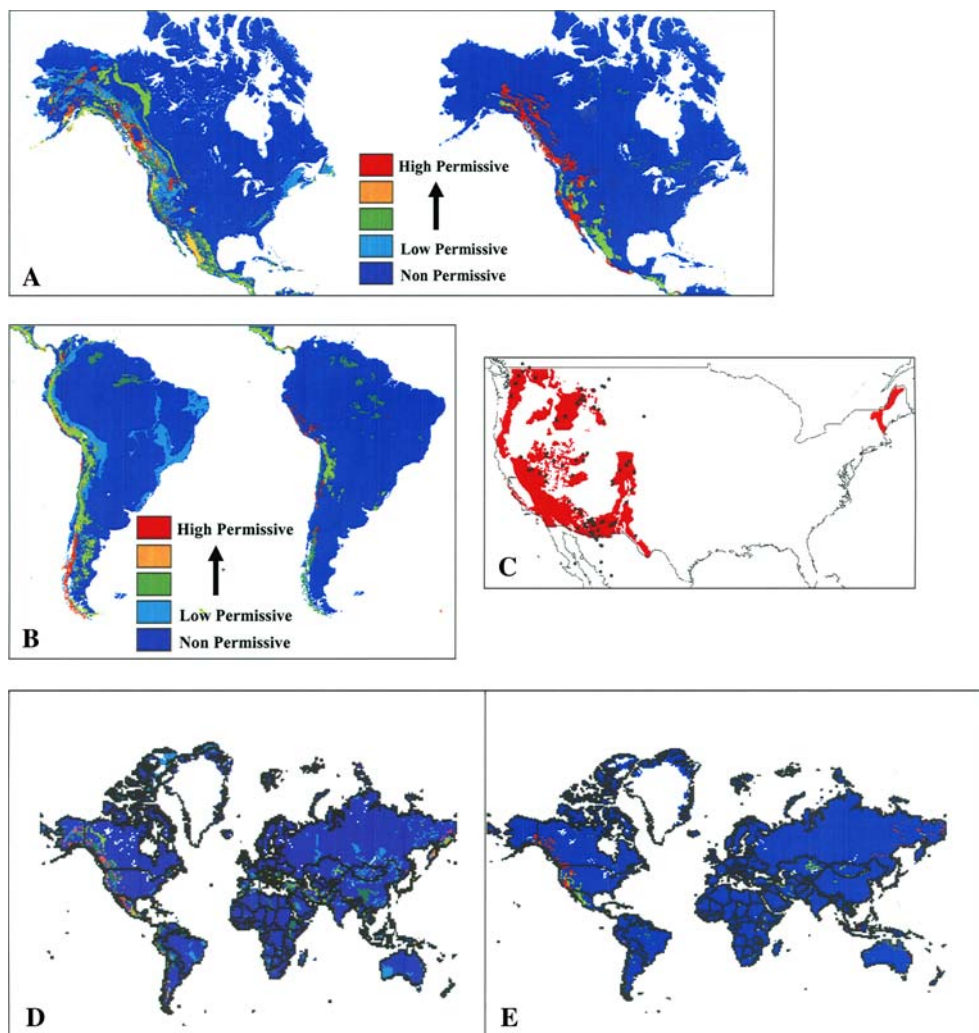


Figure 1. Comparison of Tectonic-based (Left) with F/I Igneous-based (Right) model for western hemisphere (A and B) and for globe (Tectonic-based, D, and F/I Igneous-based, E), which have same color scheme as A and B. F/I Igneous-based model defines many small areas, not well displayed in these small image. For comparison, C shows USGS porphyry tracts of United States from U. S. Geological Survey National Mineral Assessment Team (1998) with training points as black dots. In C, red is permissive and white is nonpermissive.

statistic (Bonham-Carter, 1994). Also interesting is that the kappa statistic reported by Raines and Mihalasky (2002) is intermediate between the Tectonic (lowest kappa) and the F/I Igneous (highest kappa). Kappa is significant because it makes an adjustment for the expected correlation, which is particularly relevant when concerned with rare events such as mineralization. These kappa values are considered “fair agreement” by the criteria of Landis and Koch (1977), but in the author’s experience in spatial applications such kappa values are substantial. Thus the anticipated decrease in correlation with decreasing map scale does not occur.

Another way to evaluate the differences between the Tectonic and F/I Igneous map models versus the USGS tracts is to compare the rankings of states of the United States (Fig. 2). The states are ranked by percent permissive area. The coefficient of explanation, R^2 , for the Tectonic map versus USGS tracts is considerably lower than that reported by Raines and Mihalasky (2002), but for the F/I Igneous map model the R^2 is the same reported by Raines and Mihalasky (2002). It has been suggested that this ranking test result is simply a consequence of the size of the states. This was tested by using the states as evidence and ranking

Table 3. Correlation of the Small-Scale Models with the USGS Tracts of the United States

US		Tectonic			US		F/I Igneous		
		N	P				N	P	
Expert	N	76.5	9.6	86.1	Expert	N	80.1	6.0	86.1
	P	6.8	7.0	13.9		P	6.2	7.7	13.9
		83.3	16.7	84/36/30			86.3	13.7	88/49/39

The tables show the cross tabulation or confusion matrix with percent area for the two comparisons. The agreement, kappa, and Jaccard's C are shown respectively with units of percent in the bottom right of the matrices. The margin sums are highlighted in gray. The statistics reported by Raines and Mihalasky (2002) for the 1:2,500,000-scale map are agreement (87%), kappa, (40%), and Jaccard's C (28%).

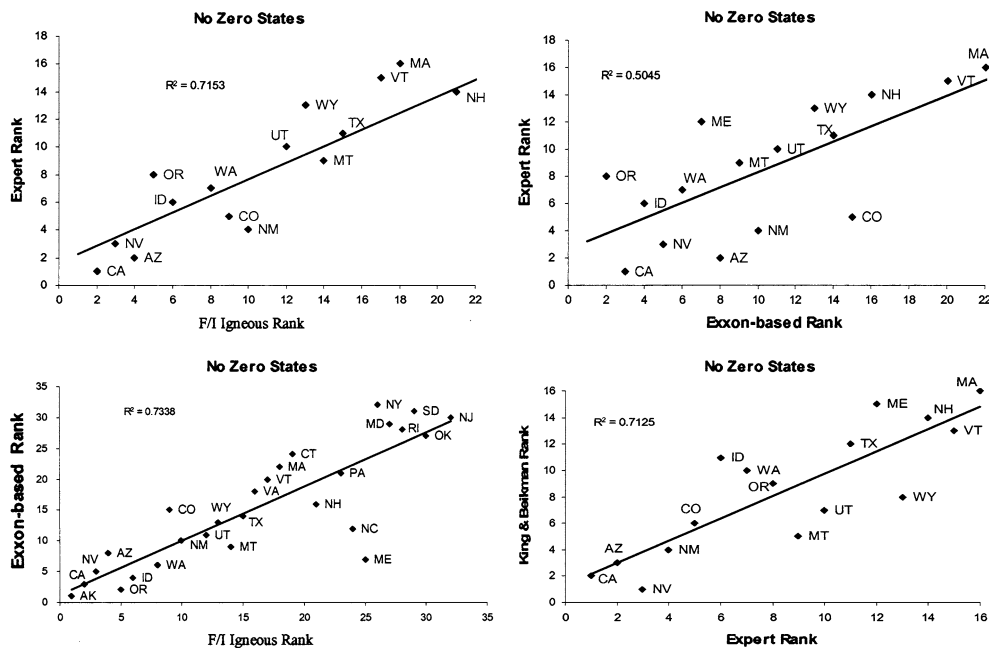


Figure 2. Comparison of states of United States ranked by area of permissive terranes by different models. Generally, ranking of states is highly correlated with that of USGS tracts, two models reported here are highly correlated, but correlation does not decrease with decreasing scale. Bottom-right plot derives from Raines and Mihalasky (2002). Those states with no permissive areas are excluded from these plots because inclusion of such states simply inflated the correlation with no meaningful change. Linear regression lines and coefficient of explanation are shown on each graph.

them by the association with the training points. The ranking defined by states as evidence had no correlation with the rankings from the porphyry models. The King and Beikman model from Raines and Mihalasky (2002) had the highest R^2 of 0.26 and the others had R^2 less than 0.1 with the states model. Thus, this test also fails to show the antic-

ipated decrease in correlation with decreasing map scale.

CONCLUSIONS

On the basis of the analyses in Raines and Mihalasky (2002), which used the King and

Beikman geologic map of 1:2,500,000 scale, and the analyses presented here of the 1:10,000,000-scale Tectonic map and the 1:35,000,000-scale F/I Igneous map models, the utility of a geologic map for predicting porphyry deposits cannot be correlated directly with the map scale. Indeed, in this study, the smallest scale map correlates best by all measures with the USGS tracts. It would seem that the conceptual focus, or theme, of the geologic map is as, or more, critical than the scale. In geophysical maps, as reported by Nykanen and Raines (2007), and probably in other maps portraying measured data, map scale is truly a measure of the size of features that can be represented. Geologic maps are illustrations of geologic relationships and the map maker subjectively selects the information to portray, sometimes exaggerating important features, in order to convey a vision or representation of features. The approach is somewhat analogous to the way a state or national highway map exaggerates the land area occupied by roadways. The conceptual framework of a geologic map is as critical as map scale in determining the utility of a geologic map for some applications. We have demonstrated that geologic maps of small scale can provide useful information, despite the decrease in spatial accuracy, for regional mineral tract definition on national and global scales. The utility of a particular geologic map for a particular application is critically dependent on the alignment of the intention of the map maker with the application, regardless of map scale.

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