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THE SEARCH FOR A MORE REALISTIC METALLOGENIC MAP FORMAT, WITH REFERENCE TO THE PINE CREEK GEOSYNCLINE

Peter Laznicka*

The format of most existing metallogenic maps is not adequate for scales of 1:500 000 or less. The major problem is the colourful out-of-scale locality symbols, which mask the map detail in the most important areas, the immediate vicinity of the ore occurrences. The design of the symbols is also a problem, most being influenced considerably by genetic interpretations that are subjective and change with time; they are incapable of expressing transitionality, correlation of metallogenetic and lithogenetic events, and they cannot accommodate incomplete information. A substantially different philosophy of metallogenic mapping has been tested using the Pine Creek Geosyncline as an example. Ideally, the product would be a set of three matching maps. Map 1 would be a base map, a modified geological map that consistently shows the age of units by colour and the lithology of units by pattern, regardless of genesis and the level of emplacement. Mineralised occurrences would be identified in the simplest way possible, so as not to obscure the background information. Map 2 would be a gitological map, or map of mineral deposits, providing information on the geological properties of occurrences. The symbols suggested are based on simplified geological cross-sections, and are colour and pattern coordinated with the base map, to give the reader an immediate impression about the contemporaneity of rock-and ore-forming events and of the hosts to the ore. Within the symbol framework for a given 'mineralisation style', a wide range of properties of individual occurrences can be shown, and unknown information can be truthfully expressed as a blank component of the symbol. Map 3 would be a commodity map, showing the ore metals, their individual and total accumulations, and the concentration of the major metal.

Introduction

Metallogenic, metallogenetic, or metallotectonic maps show the nature and distribution of mineral deposits in a geological or tectonic framework (e.g. Lang, 1961; Shatalov & others, 1966). Despite their almost 80-year history of development (de Launay, 1907, 1913), of which the last twenty years have been a period of accelerated development, metallogenic maps have not yet acquired a universally accepted style, as have geological maps. And despite the existence of the International Subcommission for the Metallogenic Map of the World and its efforts to produce a uniform global map, national institutions such as geological surveys continue, independently, to prepare metallogenic maps of their countries or continents, consistent with their local experience, needs, and traditions. The new Metallogenic Map of North America at 1:5 million (Guild & others, 1980) is an example. Here, 'the compilers of this map have departed from conventional practice and devised a legend which requires a little study to comprehend'.

The Bureau of Mineral Resources produced a Metallogenetic Map of Australia and Papua New Guinea at a scale of 1:5 million (Warren, 1972), and, although this project was aimed at producing a map modelled on the Metallogenic Map of Europe (Comité de la Carte Métallogenique de l'Europe, 1968–1973), the final map was considerably modified to suit the local conditions — for example, it incorporates the distinct Australian tectonic divisions and their unique cartographic expression.

Among the Australian states, only New South Wales has under way an ambitious program of metallogenic map production on the scale of 1:250 000 (1:50 000 for the Broken Hill area), and the Lachlan Fold Belt has now been completely covered. Mapping continues in the New England Belt, and production of metallogenic maps of large regions and orogenic belts is planned (Suppel, personal communication, 1981). Bowman & Stevens (1978) comprehensively summarised the objectives and achievements of the New South Wales metallogenic mapping program, and discussed in detail the philosophical problems of metallogenic mapping.

There is a considerable variety of metallogenic maps, and Bowman & Stevens (1978) provided a good review of eleven of them. To these should be added the recently released Metallogenic Map of North Americal (Guild & others, 1982) and the Metallogenic Map of the U.S.S.R. (Grushevoi & others, 1971).

Despite differences in detail these maps have many common features: all use a tectonic or geologic map base reduced in detail; all have over-sized, out-of-scale symbols of mineral occurrences, many of variable size to indicate the importance of the locality; and all use colour of the locality symbol to show the commodity. The maps are colourful and give a very forceful, instant picture of the regional commodity distribution in a broad tectonic or geologic framework.

Most existing metallogenic maps are compilations of national territories (e.g. Finland, Japan, Iran, Brazil), continents (Europe, North America) or both (Australia), and are one-of-a-kind maps. They have been prepared not only for geologists, but for the general public as well. All are overview maps, showing only a fraction of the existing localities.

A minority of metallogenic maps are based on topographic map sheets of more detailed scale and have been issued as one-of-a-kind (e.g. Rouyn-Noranda area, Canada; Sharpe, 1968) or as part of a series (e.g. the Carte des Gites Mineraux de la France, 1:320 000; Metallogenetic Map of New South Wales 1:250 000). These maps are designed more exclusively for geologists. One would expect such maps to show all mineralised localities and aim at the most faithful representation of the relationship of mineralisation to geology. Yet they use the same techniques and symbols as the national and continental overview maps: the French maps are striking and lavish, the New South Wales maps more subdued. A first size category ore deposit on the French map, for example the Romanéche Mn vein on the Lyon sheet (Permingeat, 1963), is a small deposit by Australian standards (408 330 t ore; Lougnon, 1956). Yet its 14-mm diameter symbol solidly covers about 30 km^2 of the map. The actual outcrop area of Romanéche veins does not exceed 0.1 km^2, so the symbol is at least 300 times exaggerated. Because the centre of the symbol corresponds to the precise geographic location, the geological information in the background map is obscured in the most important area. As a consequence, the enclosing rocks have had to be shown by additional graphic symbols, which are inconspicuous, poorly legible, and difficult to locate in crowded areas. Such maps have a reduced usefulness in mining exploration.

*Department of Earth Sciences, University of Manitoba, Winnipeg, Manitoba, Canada, R3T 2N2

In this paper I am proposing a new approach to the compilation of metallogenic maps, drawing on my experience in preparing a manuscript metallogenic map of Australia and illustrating it by reference to the metallogenesis of the Pine Creek Geosyncline.

A manuscript metallogenic map of Australia

In 1973, compilation was completed of a manuscript metallogenic map of Australia. This map was the product of experimentation on the compilation of global and continental metallogenic maps, using a computerised data base of metallic deposits of the world, MANIFILE (Laznicka, 1975). Australia was selected as a pilot project because of the unique availability of up-to-date published information on its mineral deposits (Edwards & others, 1953; McAndrew & others, 1965; McLeod, 1965; Knight & others, 1975) and the geographic, political, and economic unity of such a large territory. MANIFILE 2, used for the Australian project, included over 800 Australian deposits, compiled from the literature, with about 20 per cent of the localities checked in the field. The map, at a scale of 1:5 million, includes numerous improvements and modifications, departing from the pattern of existing metallogenic maps available in the early 1970s (Fig. 1). The changes were designed to improve map readability, and to make it more realistic, factual, and as independent as possible from the rapidly changing genetic and geotectonic models. Particular emphasis was directed towards colour coordination, which is used exclusively to show geological age: age of rock generation, rock deformation, and ore deposit formation. Other information, some highly quantitative and based on computer plots, is expressed by a variety of symbol shapes and patterns.

Base map

The base map is essentially a stratigraphic-facies map compiled from published sources, rather than a tectonic map, as used on most conventional maps. This was chosen to remove an important aspect of conceptual impermanency and subjectivity, so common with tectonic divisions. The colour of a unit indicates the geological age of its orginal lithogenesis, i.e. its 'first formation', and is the same for supracrustal (sedimentary and volcanic) and subcrustal (intrusive) rocks. The relative abundance, by 1970, of isotopic ages of most intrusive and metamorphic units made the traditional legends of geologic maps, which colour supracrustals by their stratigraphic age (e.g. Devonian, Lower Proterozoic) and intracrustals by their lithology (e.g. granite, gabbro), obsolete. The new design makes the relationship of contemporary rocks, although of different geneses and emplacement levels, immediately obvious. This is necessary for showing the background to metallogeny, because mineralisation is usually a product of lithogene interactions at different depths.

Geological units with complex history (mainly the 'geosynclinal' and 'basement' units) are shown in solid colour, representing their depositional age, over which are superimposed: patterns indicating post-depositional modification (deformation, metamorphism, granitisation), drawn in a colour corresponding to the age of such a process; patterns indicating lithologic association/facies (e.g. continental epiclastic coarse sediments, shallow marine carbonates, mafic submarine-volcanic-sedimentary associations, etc.), drawn in a neutral colour.

'Unmodified' (i.e. undeformed, unmetamorphosed) rock units, such as the late or terminal products of local lithogenesis (e.g. post-kinematic 'granite' intrusions, platformic sediments, etc.), are shown by a lithologic pattern, colour corresponding to the formational age, over a white background. Both the lithologic and modification (e.g. intensity of metamorphism) patterns are arranged in the geologically true trend.

Locality symbols

The out-of-scale symbols are superimposed on the base map, and consist of:

(1) a geographic location point, which may be obscured by the metal ratio rosettes, in which case it is their centre.

(2) Genetic/orebody shape/ore substance distribution/mineralisation symbol, located in the central part of the composite symbol. This is similar to symbols used on conventional metallogenic maps. Its geometry indicates orebody shape/mineralisation type; its orientation corresponds to the actual orientation of elongated orebodies; and the inside of the symbol may show the type of ore distribution (e.g. disseminated, banded, massive) by a black pattern. The colour of the inner symbol represents the age of mineralisation, and is a darker shade of that indicating the geological age of the rock unit on the base map. This immediately indicates the genetic relationship of the ores with the phase of development of the host rocks. Three relationships are common: (a) colour of the ore symbol corresponds to the 'depositional' age of the host unit, representing contemporaneity of rock and ore deposition (e.g. as in stratiform deposits); (b) colour of the ore symbol corresponds to the age of deformation or adjacent intrusions, representing magmatic or postmagmatic mineralisation, tectonometamorphic mobilisation, etc; (c) colour of an ore symbol located in a 'basement unit' corresponds to the colour of a nearby undeformed 'cover unit', representing mineralisation resulting from basement reworking by young near-surface agents, e.g. placers or mineralised laterites (The size of the inner symbols is uniform, regardless of the economic importance of the locality).

(3) Magnitude of mineralisation/grade category/metals information occupies the perimeter of the genetic symbol, and is significantly different from that on existing maps, both in the type of units used and the method of expression. The unit of magnitude of metal accumulation (ore deposits's 'size') is a 'ton-accumulation index' (Laznicka, 1970; see Fig. 1 for explanation) based on the mean crustal content of metals as a standard. This is an abstract unit that involves considerable calculation, and is, therefore, most conveniently derived from computerised data bases. Its initial disadvantage is that the user must become familiar with its derivation before using the map, but this is far outweighed by the unit's relative permanency (it changes only with revision of clarke values, and is insensitive to change of economic indicators, such as fluctuating metal price), and a rational logic in expressing cumulative magnitudes of polymetallic deposits. The tonnages of contained metal, or dollar values, are read directly from a set of graphs.

The anatomy and derivation of the metal/magnitude portion of the map symbol follows from Figure 1. Every metal is assigned an azimuth and shown by a spike in the map symbol. Twelve can be clearly accommodated in a single set, and membership in sets is distinguished by different patterns of spike; for example, a spike pointing 60° (ENE) represents tungsten if drawn as a solid line, and cobalt if dashed. The length of spike represents a 'ton-accumulation index' (quantity) of each metal in the ore deposit, and its magnitude can be obtained from a continuous, logarithmic scale. The outer ring represents the composite magnitude of an ore deposit, and is the sum of ton-accumulation indexes of constituent metals, based on the continuous log scale. The magnitude of metal concentration (ore grade) of the major metal is expressed by the pattern of the inner circle.

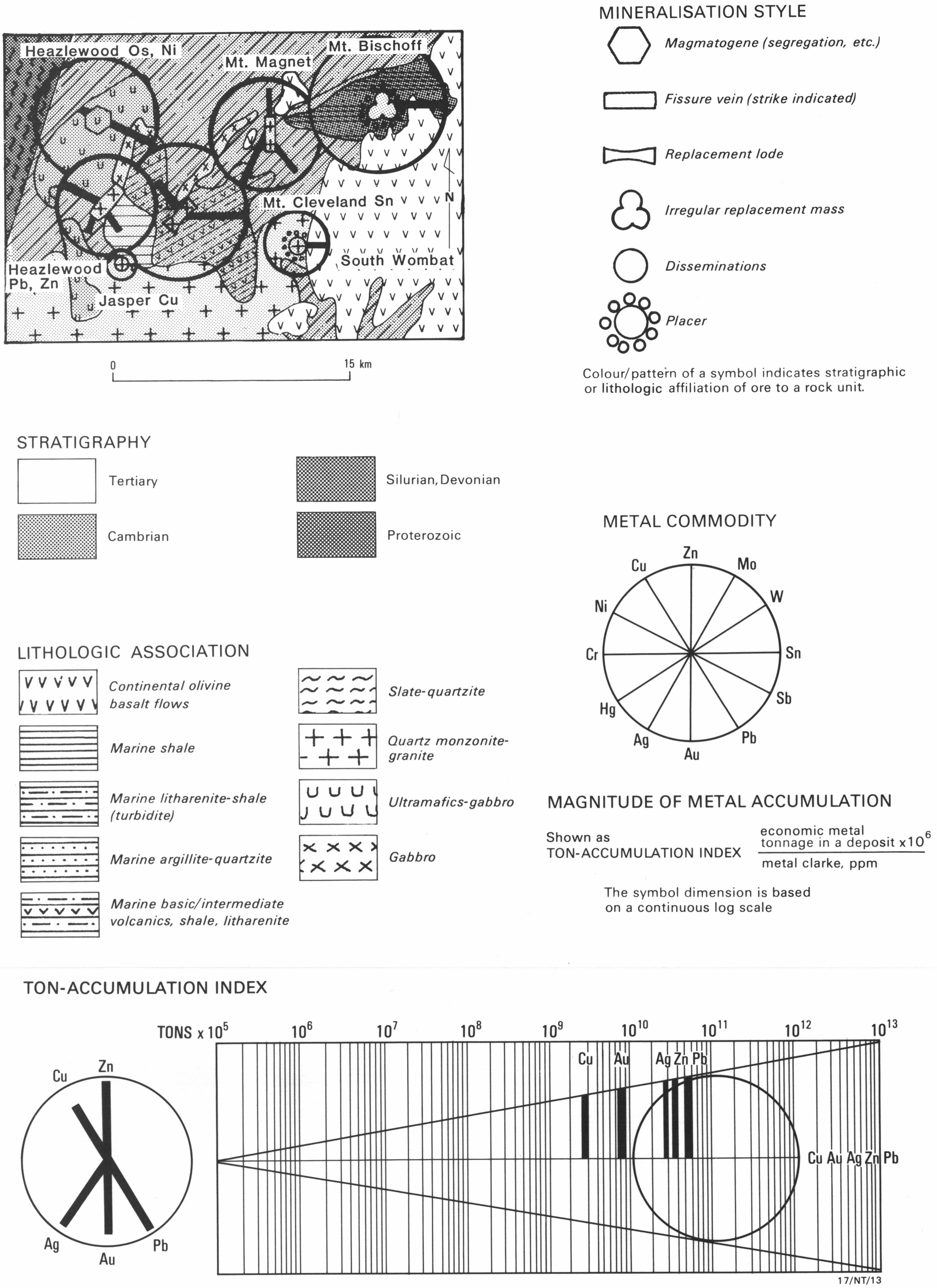


Figure 1. Manuscript metallogenic map of Australia, 1973. An inset showing the Waratah-Luina area, N.W. Tasmania, and its legend.

The manuscript metallogenic map of Australia has been demonstrated to a limited number of potential users, most of them practicing exploration geologists. Their reaction has been favourable. The colour of mineralisation age, matching the colours of lithogenesis, metamorphism, etc. in the base map, has been found to be extremely helpful for exploration and metallogenic assessments, and superior to the colour application on previously existing metallogenic maps. However, some short-comings have been noted. The metal magnitude and ratio symbols do not stand out sufficiently against the geological background, and their black colour interferes with fault lines as well as with geographic information. The symbols are particularly difficult to read in crowded areas, but this is a problem with all kinds of metallogenic maps, and not yet sufficiently solved. The manuscript metallogenic map of Australia also does not show localities of nonmetallics and fuels. Over all, experience with the map showed the need for further experimentation and this, in turn, showed that the amount of information incorporated in an ore deposit symbol had long since reached its limit. Suggestions for the future favour a series of metallogenic maps, illustrating particular aspects of ore deposits, plotted over either a uniform map base or, alternatively, several base maps giving different geological or geochemical backgrounds.

Metallogenic maps with geologically more realistic symbolism

If the style and symbolism of existing metallogenic maps is ignored and a search started for the most realistic graphic representation of an ore occurrence on a metallogenic map, a geological section of such occurrence comes as an obvious solution. A locality section that is coordinated by colour and pattern with its geological base map can present the most faithful image of the spatial and temporal relationship of the ore with its surroundings, almost free of the compiler's subjective input. To show the necessary detail, however, most sections have to be prepared on a more detailed scale than that of the base map. However, there are two formidable groups of obstacles to this: (1) incompleteness of data; and (2) limitations in cartographic expression.

Incompleteness of data

In an area such as the Pine Creek Geosyncline, three categories of ore occurrence, arranged by decreasing completeness and reliability of information, can usually be recognised: (1) well-studied and recently described localities, most of which are operating mines or economic deposits ready for production (e.g. Ranger, Jabiluka, Koongarra, and Nabarlek deposits in the Alligator Rivers district); (2) partially studied and described localities, most of which are small former producers (e.g. Mt. Bundey — Fe; Cosmopolitan Howley — Au), and localities that are part of clusters of ore occurrences of similar type, but different in detail (e.g. localities in the Maranboy Tinfield, Pine Creek — Union Reefs Goldfield, etc.); and (3) small occurrences, inaccessible mines, and recent confidential discoveries, on which very little reliable data are available (e.g. the numerous numbered Ranger prospects in the Jabiru area).

Only localities in category (1) and a few localities in category (2), about 40 out of the total of approximately 520 on the Pine Creek Geosyncline map sheet, would provide sufficiently accurate individual geological sections that could be directly incorporated onto the map. Of the rest, about 65 to 75 per cent are understood to the extent that simple category symbols showing mineralisation style, host rocks, and age of mineralisation could be prepared. The precise dimension, orientation, and characteristics of mineralisation are not known well enough to be shown. The meagre information available for the remainder of occurrences makes it possible to plot only their geographic location together with name and commodity symbol. As a result, a metallogenic map based on the above philosophy would have three categories of symbols by completeness, a solution that preserves the highest possible degree of realism, but also one likely to be criticised by advocates of metallogenic map uniformity.

Uniform map symbols

Uniform symbols for mineralised occurrences based on the above data and principles can be obtained only if: (1) only the information available for all ore occurrences is included; (2) missing pieces of information are replaced by assumption; or (3) only information-rich localities are shown, and others excluded.

'Minerals Maps', such as the U.S. Mineral Investigations Resource Maps (e.g. Koschmann & Bergendahl, 1962) correspond to category (1) and show occurrences as location plots broadly graded by tonnage and an index number and/or name of locality. Most existing metallogenic maps are a combination of categories (2) and (3).

In detailed metallogenic maps of areas such as the Pine Creek Geosyncline, it is required that all localities be shown. On the other hand, the variety of mineralisation is considerably less than on metallogenic maps of entire continents, and most localities, although not necessarily described in detail in the literature, can, nevertheless, be assigned to a certain local mineralisation style be and given a symbol on the metallogenic map.

The concept of ore (mineralisation) types has recently been reviewed (Laznicka, 1981) with the conclusion that, despite a degree of inaccuracy, ore types are useful in regional metallogenic studies, if they are adequately defined and only similar size categories are considered together. Mineralisation styles are looser groupings of occurrences that, despite many similarities, are too heterogenous to enable a single representative locality to be selected.

Table 1. Characteristics of mineralisation styles, Pine Creek Geosyncline.

Code	*Metals*	*Characteristics*	*Example localities*
S	Pb,Zn,Cu (Au,Ag)	Pyrite, pyrrhotite, sphalerite, galena, chalcopyrite, disseminated to massive banded, form stratiform lenses in carbonaceous (black), dolomitic or siliceous, marine volcanogenic low-grade Lower Proterozoic metasediments.	Iron Blow Mount Bonnie Rum Jungle-Embayment
	Au (Ag,As)	Gold-bearing pyrite, arsenopyrite and minor base metal sulphides disseminated in stratiform lenses, in the same association as above.	Golden Dyke
M	Pb,Zn,Cu (Au,Ag)	Sphalerite, galena, chalcopyrite, pyrite etc., in dolomite, quartz, etc. gangue form transgressive veins in the same association as the S style, from which they may have developed by remobilisation.	Woodcutters
	Au (Ag,As)	Quartz, pyrite, arsenopyrite, gold and minor base-metal sulphides, transgressive veins occuring in the same association as Fleur de Lys the S style, from which they may have developed by remobilisation.	Cosmopolitan Howley Fleur de Lys

G_1	Sn,W (Ta,Nb)	Scattered and disseminated cassiterite + wolframite in metasomatic pegmatites, often grading to greisens, in or near to granitic plutons. Locally abundant tantalite and lithium silicates.	Mountain View (W) Mt Finniss Mt Tolmer
G_2 G_3	Sn(W)	Disseminations (G_2) and stockworks of veinlets, of cassiterite + wolframite in altered granite. Transitional to G_2, G_4 and G_5.	Yeuralba (partly)
G_4	Sn,W	Scattered cassiterite and/or wolframite, arsenopyrite, chalcopyrite, etc. in quartz-mica 'katathermal' veins within granite.	Yeuralba (partly)
	W,Mo	Wolframite and molybdenite scattered in quartz veins within altered aplite dykes intruding a granite stock	Yenberrie
G_4	U	Torbernite, autunite, hematite + apatite disseminations and small quartz veins in silicified shears and fractures in granite.	Fergusson R Edith R.
G_5 G_6	Sn,W (Cu)	Quartz, cassiterite + chalcopyrite, arsenopyrite, etc. fissure 'katathermal' veins proximal to granite plutons.	Mt Wells Maranboy Yeuralba
G_7		Hydrothermal ('mesothermal') fissure veins and mineralized tectonic breccias, occurring in the thermal aureole of granitic plutons, with which they appear to be coeval. Transitional to 'M' style.	
	Pb,Zn(Cu)	Quartz-galena, sphalerite (primary), abundant secondary cerussite, smithsonite, hydrozincite, etc.	Mary River Coronet Hill, Minglo, etc.
	Cu	Quartz, chalcopyrite, pyrite (primary) abundant secondary malachite, azurite, chrysocolla, cuprite, chalcocite, etc.	Mt Diamond, Mt Ellison, Daly River
	Au(Ag,As)	Quartz, pyrite, arsenopyrite, minor base metal sulphides	Northern Hercules
	U (Cu)	Quartz, pitchblende + pyrite, chalcopyrite secondary torbernite, autunite	Adelaide R. George Creek
G_8	Pb,Zn,(Cu)	Replacement bodies in carbonates, in same setting and transitional into G_7.	Evelyn
G_9	Au	Quartz, pyrite, arsenopyrite, gold, shear, cleavage, and fissure-controlled open space filling and replacement veins, in tightly folded slates and greywackes in embayments near granite massifs	Pine Creek-Union Reefs
U	U(Au,Cu)	Dispersed, disseminated, fracture coatings, veinlets, veins of pitchblende, and a variety of secondary U minerals, in places with Pb, Zn, Cu, Ni, Co sulphides and arsenides and with gold. Form shallow, tabular to irregular orebodies preferentially in retrogressively metamorphosed, sheared, and brecciated schists and associated carbonates, chlorite and hematite altered, close to unconformities and basement massifs.	
U_1	U(Au)	In metasediments, close to unconformity.	Ranger I Jabiluka

U_2	U	In metasediments, under unconformable cover of Carpentarian sediments.	
U_3	U	In metasediments, under cover of Cretaceous sediments.	Ranger 68
U_4	U	In erosional basement window, narrow tabular orebodies, high grade host metamorphism obscures Archean basement relationships.	Nabarlek
U_5	U(Co,Ni Cu,Pb,Zn)	In metasediments, relationship to unconformable cover rocks weaker.	Rum Jungle
U_6	U(Au)	In Carpentarian cover rocks.	partly El Sherana, etc.
R		Residual mineralisation developed at paleosurface.	
R_1	Fe	Massive to porous hematite and minor limonite overlying ferruginous and pyritic slates and schists.	Frances Creek Mt Bundey
R_2	Mn	Porous Mn oxides overlying siltstone regolith.	Green Ant Cr.
D_1	Sn(W)	Cassiterite in alluvial placers usually close to the bedrock source.	Mt Wells Myra Falls
	Au	Gold in proximal alluvial placers.	Pine Creek
D_2	Ti,Zr,Fe	Distal beach placers of heavy minerals (magnetite, ilmenite, rutile, zircon).	Point Blaze
D_3		Paleoplacers — detrital heavy minerals in consolidated sediments.	
	Th,REE	Thorianite, monazite in Proterozoic sandstones.	Crater, Crusader
	Fe,Ti	Ilmenite, titanomagnetite in Proterozoic sandstone and siltstone.	Kapalga

Compiled from data in Crohn (1968), Needham & Roarty (1980) and Needham (1981 — unpublished thesis).

Table 1 lists a suggested selection of mineralisation styles distinguished in the Pine Creek Geosyncline, and Figure 2 shows the corresponding geological section symbolisation. In contrast to the classification of mineral deposits in the Pine Creek Geosyncline proposed by Needham & Roarty (1980), no stratigraphic position is emphasised here, because it is variable and apparent from each individual map symbol.

Because of the considerable degree of subjectivity in introducing the mineralisation styles, it is preferable that their scope be broad rather than narrow, and that boundaries of mineralisation styles be based on distinct natural breaks, if at all possible, rather than on an accessory variation within a broad, transitional series of deposits.

Figure 3 compares the mineralisation-style symbols with the actual geological sections of twelve uranium deposits, members of the U category in Figure 2. Considerable variation in shape and position of individual ore bodies, local tectonic structures, immediate host rocks, size, etc. is obvious. It is, however, also clear that the variations are transitional and that only a few features are sufficiently strong or individual to justify a sensible subdivision of this mineralisation style into several sub-styles. Some localities appear to be the result of mixing of two or more mineralisation styles, for example, the Embayment mineralised zone at Rum Jungle (Dyson's and White's ore bodies; Fig. 3), where the U and S styles overlap. Elsewhere, two distinct mineralisation styles contribute to production or reserves at a single locality (e.g. tin- bearing veins and placers, as at Mt. Wells).

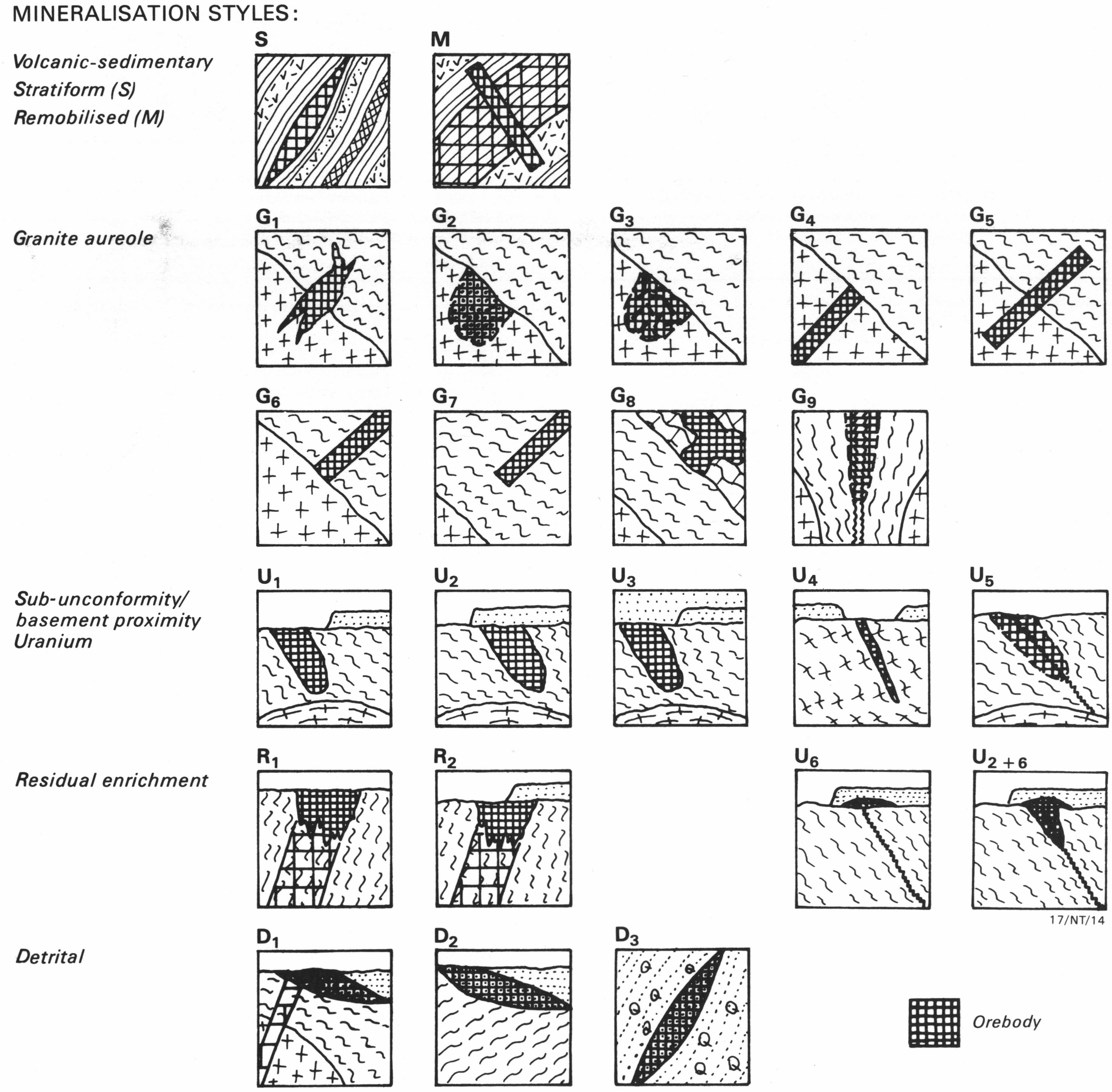


Figure 2. Suggested symbols for mineralisation styles, Pine Creek Geosyncline map.
(See Table 1 for the description of coded styles).

It is important to note that the geological section symbols do not indicate genesis. Vein deposits located in a 'granite' aureole (Fig. 2, category G) are distinguished by their position relative to the 'granite' contact and their approximately coeval relationship with the 'granite' is shown by the same 'age' colour. The reader is, however, not being pressed into accepting that the veins have been filled from below, from above, or laterally, or that the ore substance has been supplied by the 'granite' or from elsewhere. This gives him the freedom to decide according to his own belief and the latest genetic model in force. Elimination of the genetic aspects from locality symbols makes metallogenic maps more durable, credible and almost immune to the continuous change of genetic ideas.

Section-style locality symbols are especially convenient for multistage and genetically complex ore occurrences, which, on conventional maps, are displayed only as products of the very last generation or regeneration process. For example, the symbol for proximal detrital deposits (Fig. 2, category D_1) of gold and cassiterite shows the detrital orebody (placer gravel lens or sheet) as well as its primary bedrock source.

The section-style symbols have another advantage: they enable the expresssion of incomplete information and remove the need to complete it with guesses. If a locality is a vein located in a 'granite' aureole, but there is no proof that the vein and 'granite' are coeval, then the vein symbol will appear in the correct position, but its age colour will be white, that is, unknown. If the locality is an ore placer and its bedrock is unknown, only the placer part is shown in colour and pattern, whereas its bedrock remains blank.

Limitations of cartographic expression

Because of the close connection between the base map and mineralisation symbol, colour, and pattern, it is paramount that the most critical area, the immediate surroundings of the locality on the base map, is not masked by the locality symbol. This presents a formidable problem to the method of cartographic expression.

The ideal solution would be a three-dimensional map, prepared, for example, from a base map with locality symbols pinned into it (Fig. 4). A variety of arrangements for such a map would possible, but all would be cumbersome to handle and impossible to print. To achieve the objective outlined above using conventional map techniques, a set of maps is needed, and their characteristics appear in the suggestions that follow.

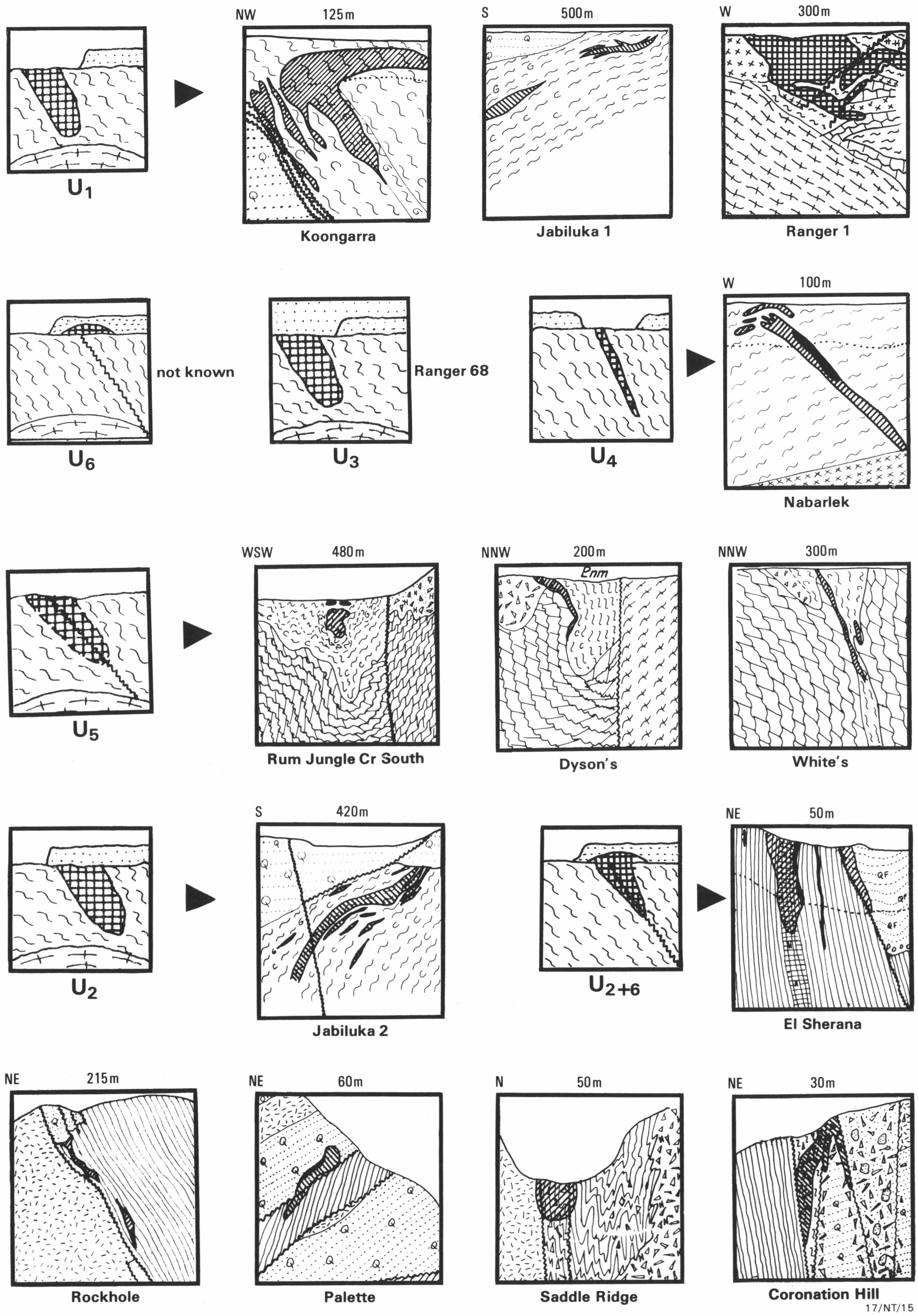


Figure 3. Comparison of mineralisation-style symbols (marked U) with the actual geological sections of twelve uranium deposits in the East Alligator River, South Alligator River, and Rum Jungle districts.
Based on data in Crohn (1968), Hegge & Rowntree (1978), Crick & others (1980), Fraser (1980), Hegge & others (1980), Stuart-Smith, personal communication (1981), and author's visits (1981).

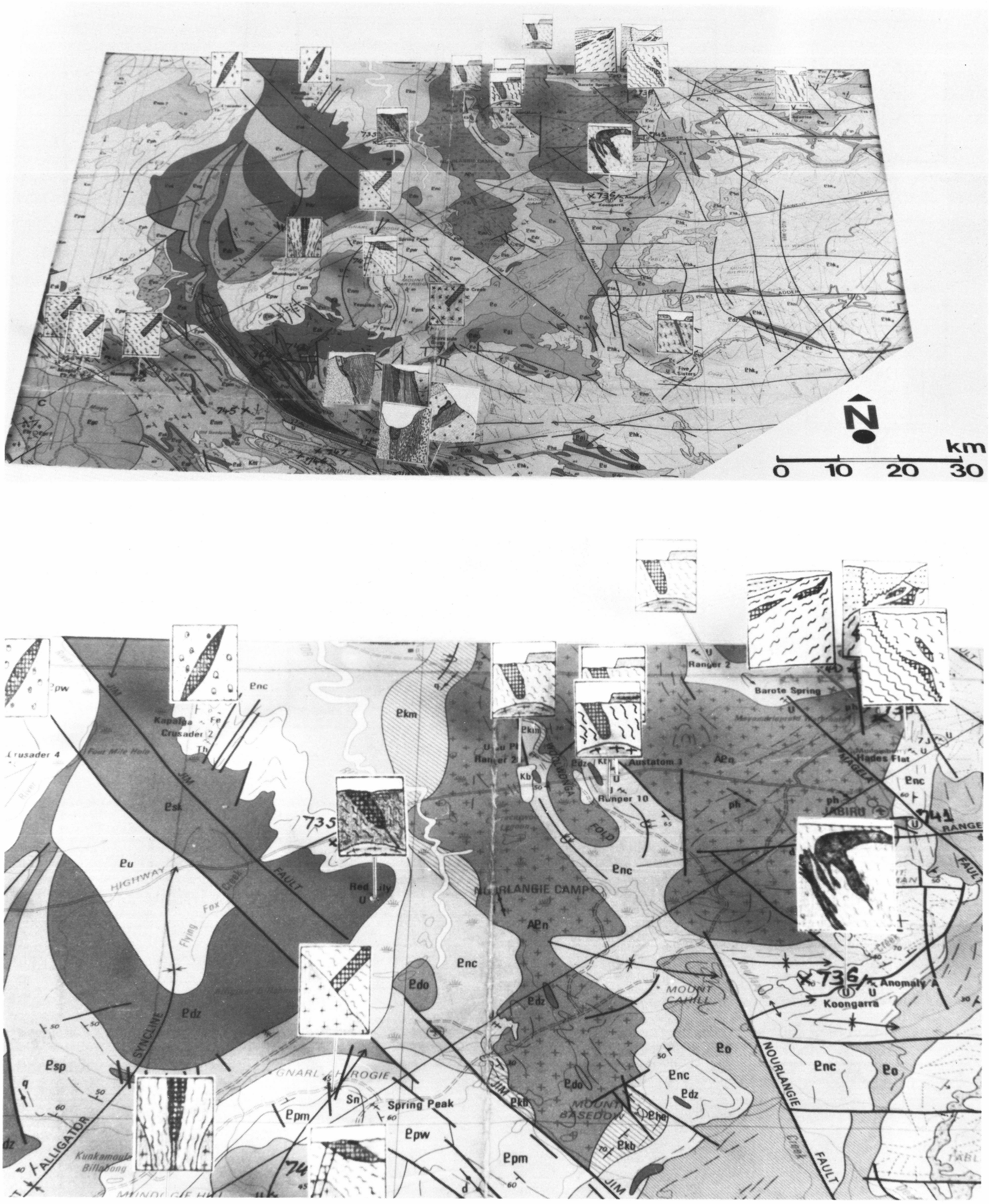


Figure 4. Three-dimensional gitological map of a portion of the Pine Creek Geosyncline, showing section-style symbols of mineralised occurrences pinned in vertical position onto the base map.

A realistic metallogenic map, illustrated by the Pine Creek Geosyncline

The regional geology and mineralisation in the Pine Creek Geosyncline have been summarised by Walpole & Crohn (1968), Crohn (1975), Needham & others (1980), and Needham & Roarty (1980), and a coloured 1:500 000 geological map has been produced (Needham, 1979). A matching map of mineral occurrences and mineral districts accompanied by a very comprehensive data list forms part of Needham's M.Sc. thesis.

Abundant literature describes the geology of local areas, mineral deposits and occurrences in the region, and the history of ore discoveries, from the relatively small gold, tin, and lead-silver occurrences (Noakes, 1949; Sullivan, 1953), to the uranium and base metal finds in the Rum Jungle area (e.g. Roberts, 1960; Berkman, 1968), and the large uranium discoveries in the East Alligator River district (e.g. Eupene & others, 1975; Rowntree & Mosher, 1976; Anthony, 1976). The symposium volume, Uranium in the Pine Creek Geosyncline (Ferguson & Goleby, 1980), provides the most comprehensive summary and reinterpretation to date of the Pine Creek Geosyncline metallogeny, not only of uranium.

The metallic mineralisation is widely, but very unevenly, distributed, and densely mineralised fields alternate with areas devoid of mineralisation. Needham & Roarty (1980) rated the mineralisation in the Pine Creek Geosyncline by value, and concluded that almost 97 per cent of the total value is due to uranium. Significant uranium mineralisation, however, is confined to three areas only, and the East Alligator Rivers field alone accounts for over 95 per cent of the total.

Needham & Roarty (1980) subdivided the mineral occurrences in the region into five categories by type and stratigraphic association:
(1) stratabound U and U-Au deposits in the Masson and Cahill Formations close to the Archaean basement; (2) stratiform and stratabound Ag, Pb, Zn, and Cu deposits, also in the Masson and Cahill Formations, throughout the former basin; (3) stratiform Au, U-Au, Pb, Zn, and Cu deposits in the Koolpin, Gerowie, and Kapalga Formations; (4) vein-type Au, Sn, Ag-Pb, W, Ta, Cu, Bi, etc. deposits, associated mainly with the early Carpentarian granites; (5) supergene Fe and Fe- Au deposits, located mainly in the Wildman Siltstone.

Genetically, the ore occurrences form a broad sequence from single stage to multistage mineralisation. Single-stage mineralisation resulted from an almost continuous process of concentration and accumulation of one or more ore metals, initiated against an almost geochemically neutral background by, for example, the process of igneous and sedimentogenic differentiation. The tin-tungsten veins in granite aureoles, an indisputable final product of granite differentiation, represent the most obvious example, although it can be argued that the granites themselves inherited their tin specialisation from their precursors. Single-stage ores show the most obvious and intimate relation to their parent units and their development history, and easily fit into conventional metallogenic classifications (including metallogenic map symbols).

Multistage mineralisation demonstrably forms by a series of steps, where, typically, each step increases the local accumulation of ore metals, mostly by confining the former broader metal reservoir into a progressively restricted volume of host rock or a mineralised structure. A generally accepted chain of events leading to the formation of uranium deposits in the Alligator Rivers and Rum Jungle ore fields that has emerged in the past ten years (e.g. Dodson & others 1974; Needham & Stuart-Smith, 1980), has three major steps: (1) local metamorphogenic and igneous-metasomatic enrichment of uranium in the Archaean basement complexes; (2) redeposition of detritus and uranium from (1), and additional uranium enrichment in certain lithologically favourable Lower Proterozoic units, e.g. in the Masson and Cahill carbonaceous shales; and (3) economic accumulation of uranium during localised, endogenous or exogenous, retrogressive reconstitution of (2) at shallow crustal levels.

Multistage mineralisation is exceedingly difficult to accommodate in conventional metallogenic models, because each enrichment step has to be considered separately and certain steps, often the final ones, coincide with lithogenically obscure and regionally unimportant events, such as the 1700–500 Ma events that finalised the uranium deposition in the Alligator Rivers district (Dodson & others, 1974; Hills & Richards, 1976).

Much mineralisation in the region falls, by its complexity, between the single-stage veins and the multistage unconformity uranium deposit; for example, the gold ores at the Cosmopolitan Howley mine (Sullivan, 1953) appear to have an identifiable two-stage genesis, having resulted from a tectono-metamorphic remobilisation of a volcanic-sedimentary metal-enriched stratiform horizon (Needham & Roarty, 1980). Many Pb, Zn, Cu, Au, and Ag occurrences in the area appear to have a similar origin, and the proportion of the first-stage (stratiform) and second-stage (remobilised in veins or breccia) ores varies widely at different localities. No doubt, the most difficult task is the categorisation of epigenetic Pb-Zn(Cu) deposits hosted by contact-modified Lower Proterozoic supracrustals, in the aureole of the late orogenic granites (e.g. the Mary River, Namoona prospects): are they multistage products of remobilisation of stratiform metals in the host sequence or single-stage products of magmatic differentiation, independently supplied by the granite, without much contribution from the supracrustals? Problems like this fit into Krauskopf's (1968) category of 'unsolvables', problems that remain, no matter how much research is put into the attempted solution. Obviously, there is no sharp boundary between the above categories because of the widespread convergence, and there does not appear to be a practical pressing need for a solution, except, perhaps, one. This is the categorisation of genetic types of mineralisation, which, in turn, is needed for symbol construction on conventional metallogenic maps.

I believe that metallogeny of areas such as the Pine Creek Geosyncline can best be cartographically represented by a set of three maps: (1) a modified geological base map; (2) a gitological (= mineral deposits) map; and (3) a metallic map. This, however, does not take into account the practical requirements of production cost, and various modifications of the suggested format are certainly possible. One solution, suggested by the critical readers, was to place part of the information on the map margin, thus reducing the number of maps in the set.

(1) The base map is of utmost importance, and the compilers should take into account the requirements, outlined earlier, necessary for its coordination with the map bearing the locality symbols. For the Pine Creek Geosyncline, 1:500 000 would be the most suitable scale for the base map.

(2) The map showing geological properties of ore occurrences (gitological map, Fig. 5A, B) has out-of-scale symbols, placed in a uniform position in respect to the topographic location point (e.g. the point will be in the left- hand corner of the symbol, in the centre of the symbol, or offset in crowded areas, and indicated by an arrow). There is a wide selection of possible symbols, and it is thought that the mineralisation-style symbols described earlier are the most suitable for this map. The characteristics of the mineralisation styles and their limitations, however, will have to be thoroughly described on the map margin or in a companion report.

(3) The metallic (metal, commodity) map (Fig. 5C, D) shows the economically accumulated metals, their ratios, individual and composite magnitudes of accumulation, and intensity of concentration. It is suggested that the quantitative system of expression developed for the manuscript metallogenic map of Australia (Fig. 1) be used, possibly improved by the use of colour. Additional means of expression will have to be devised to show metals listed as commodities of small occurrences, where the lack of data prevents the use of the quantitative symbols. Uniform size colour dots have been used in Figure 5C, D. The background map is the same as the background of the gitological sheet.

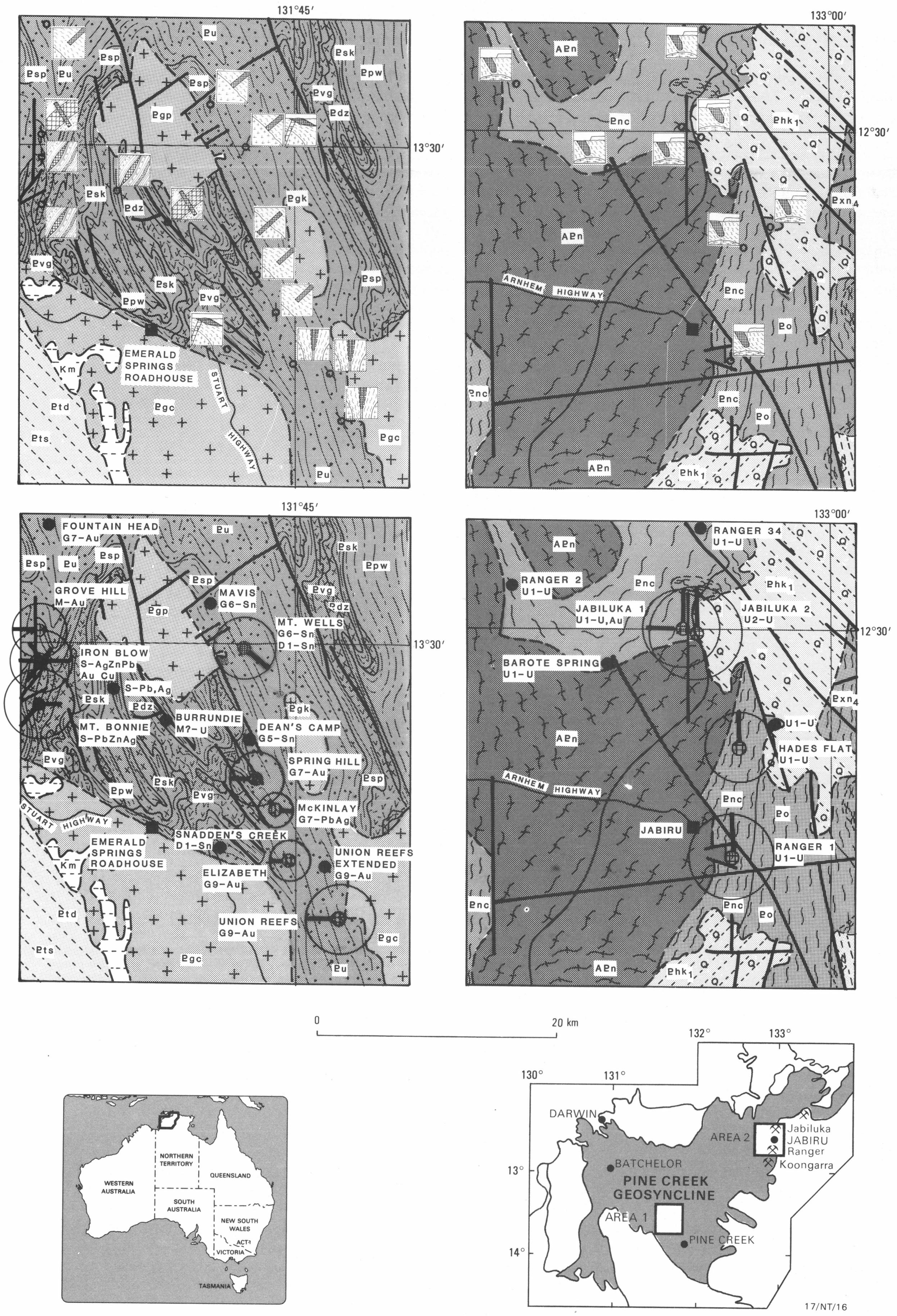
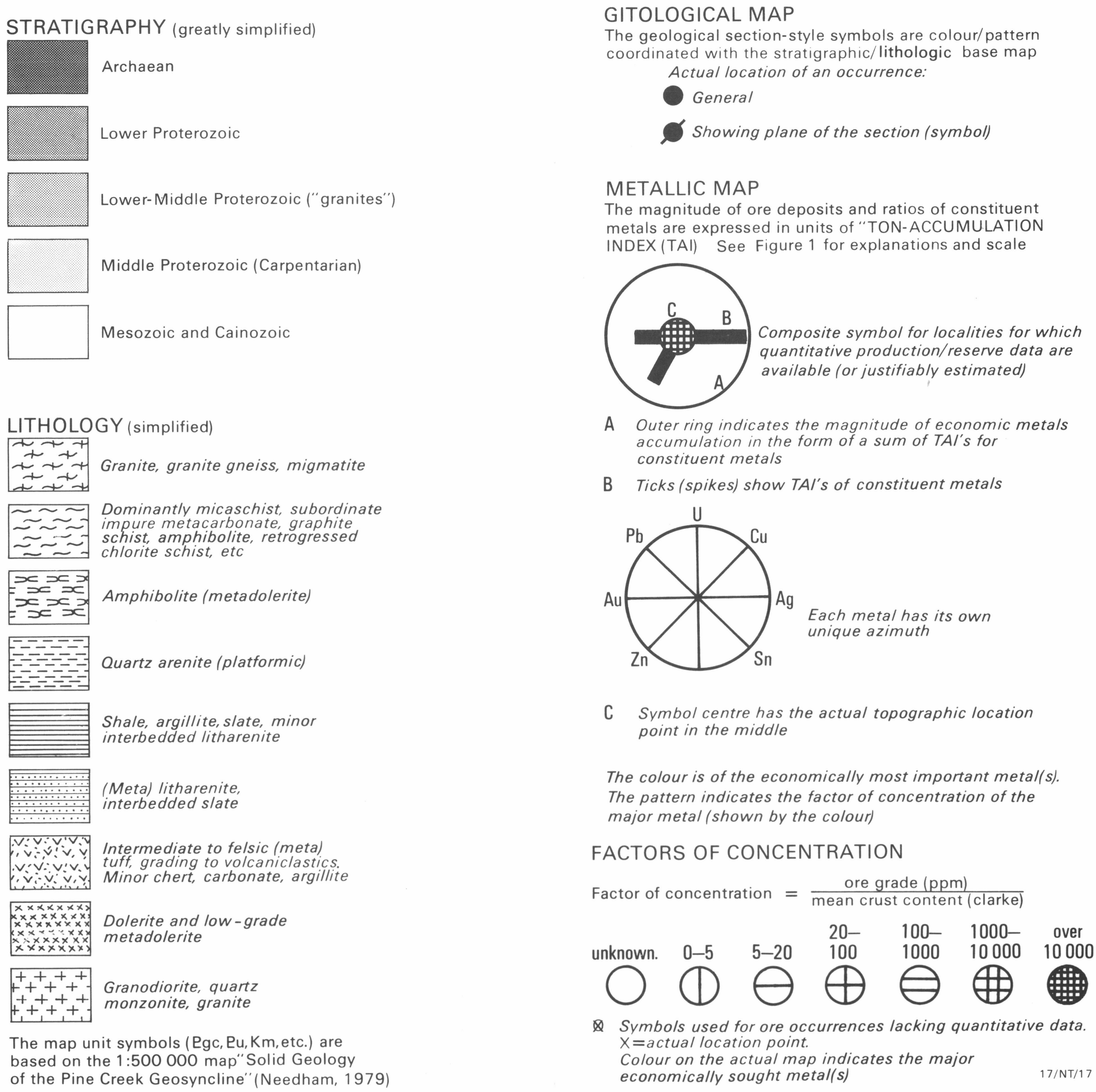


Figure 5. Two areas (Margaret Syncline — Mt Wells — Union Reefs, and Jabiru area, East Alligator River Uranium Field) of the Pine Creek Geosyncline, 1:500 000, illustrating the proposed gitologic (top) and metallic (bottom) maps, and their references.



In contrast to many existing metallogenic maps, such as the Metallogenic Map of Australia (Warren, 1972) or Europe (Comité de la Carte Métallogenique de l'Europe, 1968–1973), metallogenic contouring or hatching to show outlines of metallogenic belts and provinces is not recommended here. Given the uncertain status of the regional metallogenic divisions (e.g. Turneaure, 1955; Petrascheck, 1965; Routhier, 1980) and a multitude of factors that control them — each factor having its individual outline, contouring appears justified only on large-scale maps, where it compensates for the impossibility of plotting all (or at least most) mineral occurrences.

Other than for showing the extent of mineral deposits distributed over large areas, such as coal, bedded iron ores, bauxite, etc., metallogenic contouring does not seem justified in detailed local maps such as the Pine Creek Geosyncline. Here, the established geological controls of mineralisation follow from the geological base map: the batholiths and their aureoles, the belts or units with favourable lithology likely to contain stratabound deposits, the traces of unconformities, the Archaean basement complexes. Controls not shown by the geological map are usually hypothetical and their inclusion could mislead the reader more than help him. How, for example, would the 'Uranium metallogenic province of the Alligator Rivers' be outlined?

The value of any geological report or compilation can be further enhanced by the availability of representative rock and mineral suites for public perusal. Particularly suitable for the representation of lithology and mineralogy of a metallogenic map area such as the Pine Creek 'Geosyncline', would be the portable documentation system 'LITHOTHEQUE' (Laznicka, 1974). This is a 'library' of rock and mineral specimens arranged cemented to aluminium plates, equipped by description/legend sheets and stored in a book-like manner.

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