the main phase of hydrocarbon generation and expulsion coincided with increased heat flow and possibly extension in the Early Cretaceous. Although various sedimentary successions throughout the southern Taroom Trough undoubtedly reached maturity, the quantity and quality of the organic matter would have determined whether the resulting hydrocarbons were adequate to support primary migration from the source rock.

From an extensive geochemical database which the project developed for hydrocarbon and potential source-rock samples from the Queensland sector of the basin, an oil–source-rock correlation study confirmed a Permian source for the hydrocarbons, and a minor contribution from a local Triassic source (Boreham 1995: APEA, Journal 35, 579–612). A much smaller database is currently being compiled for samples from the New South Wales sector.

Outcome of studies: the Bowen Basin as an example

The project has documented six effective source-rock units in the Bowen Basin: the Triassic Moolayember Formation, and the Permian Baralaba Coal Measures, Burunga Formation, Banana Formation, Flat Top to Buffel Formations, and Reids Dome beds. We have assessed the individual oil and gas contributions from coal and mudrock in them. Source rocks in the Baralaba Coal Measures and the Burunga Formation have contributed over 90 per cent of the oil generated in the central Bowen Basin, and the same two units

plus the Flat Top to Buffel and the Banana Formations have contributed about 90 per cent of the gas.

The combination of high heat flow and extra sediment thickness during the Early Cretaceous accounted for most of the hydrocarbon generation, and induced the bulk of the Permian source rocks to expel oil and gas for the first time. Only in those parts of the basin where the sediment pile was thickest (particularly along the axis of the Taroom Trough) were hydrocarbons generated earlier, starting in the Late Permian but mainly during the Triassic. On the western margins of the basins in Queensland, major trap formation probably coincided with the high rate of hydrocarbon generation and expulsion in the Early Cretaceous. Maximum palaeotemperatures were evident at this time, and represent the primary control on hydrocarbon generation.

Each of the source-rock units generated hydrocarbons in discrete structurally defined parts of the Bowen Basin (Fig. 13). Also, each one forms the basis of a separate petroleum system (Fig. 14) that has now been evaluated in the central part of the Bowen and Surat Basins by Shaw (1996: unpublished report commissioned by AGSO). According to TOC areal distribution (Fig. 15a) and initial HI (Fig. 15b) for the Burunga mudrock petroleum system, for example, the combination of oil-prone source (HI >200 mg hydrocarbons/g TOC) and high organic richness (TOC >3%) would have favoured oil expulsion during the Cretaceous (Fig. 15c) only in the southeast corner of the map area. Further,

this petroleum system was the main contributor to the oil generated in the south.

Regional implications

Our estimates of the timing and products of generation, and of the relative yields of the more effective ORRs, offer insights into the potential for new plays in the region. We consider that the present-day structure is a reasonable representation of the geometry of the central Bowen Basin at the time of generation during the Early Cretaceous. Thus the distribution and character of reservoir and seal units and traps can be overlaid on potential migration pathways from the centre of the basin, particularly at the relatively unexplored eastern margin of the basin. The timing of the emplacement of trap, reservoir, and seal play elements relative to the timing of generation is documented on timing charts (e.g., Fig. 14).

In conclusion, the SBEA project has produced a consistent tectonostratigraphic framework over a large region of eastern Australia that will form the basis for regional evaluation of the petroleum systems in the Bowen, Surat, and Gunnedah Basins. A more detailed study of the central Bowen and Surat Basins suggests that at least six petroleum systems operated there, but that only two or three produced large volumes of hydrocarbons. The results suggest that large volumes of hydrocarbons might have accumulated in a number of unexplored areas in the central Bowen and Surat Basins, but offer no clues about the potential for their preservation.

Alteration mineral mapping with the laser Raman microprobe: a new technique

Terrence P. Mernagh[1] , Kenneth C. Lawrie[1], & Julienne Kamprad[1]

The laser Raman microprobe offers a new and rapid method of identifying minerals in thin sections, rock chips, and drillcore. Advantages of this method include visual selection of each mineral, spot analysis (down to 1 μm), little or no sample preparation, and the ability to identify mineral polymorphs. The Raman technique is a form of vibrational molecular spectroscopy that is very sensitive to crystal structure; hence, it can be used to identify a wide range of minerals — including most silicates, carbonates, sulphates, nitrates, phosphates, hydroxides, oxides, and sulphides. The small spot size also makes this a powerful method for the identification of very fine-grained mixtures of minerals, such as those commonly encountered in alteration zones surrounding hydrothermal mineral deposits.

Many alteration haloes show a zonation of mineral assemblages resulting from the changing composition of the hydrothermal fluid as it flowed through the host rocks. Alteration may vary from minor colour changes to extensive mineralogical transfor-

mations and complete recrystallisation. Correct identification of both the primary and altered mineral assemblages is necessary for a proper understanding of the ore-forming processes and exploration for similar styles of deposits. Often, geologists must rely on their powers of observation or simple tests (e.g., staining) to identify minerals in drillcore or hand specimens, but if these are inconclusive then more detailed laboratory procedures are required. However, the need for time-consuming sample preparation can now be obviated, as the laser Raman microprobe (Fig. 16) provides a rapid, non-destructive analysis at the micron scale of any specimen which can be placed under a microscope.

Examples of alteration styles

Porphyry Cu–Au mineralisation

In the porphyry environment, identifying mineral assemblages helps establish the relative locations of samples within the hydrothermal system. Establishing these criteria facilitates both the recognition of fluid pathways and, ultimately, the determination of

vectors to mineralisation. However, the very fine grainsize of many of the constituent minerals in these alteration assemblages can make them difficult to identify in hand specimen. Also, discrimination between alteration styles is commonly a severe problem in more oxidised systems where hematitic dusting can impart a pink colour to the feldspar alteration; this makes it difficult to discriminate between alteration containing only hematite and that with hematite-dusted feldspar (sodic or potassic).

Traditionally, identification of these fine-grained alteration assemblages has relied on a combination of thin section, X-ray diffraction (XRD) and staining techniques, and, more recently, PIMA[*] spectral data. Even

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[*] Portable Infrared Mineral Analyser (an infrared reflectance spectrometer). Note that the use of brand names does not represent an endorsement of these products by AGSO.

Fig. 16. Dr Terry Mernagh analysing a sample of rock with AGSO's Microdil 28 laser Raman microprobe.

Fig. 17. Laser Raman microprobe spectra of minerals which may occur in alteration assemblages of porphyry Cu–Au deposits.

Fig. 18. Laser Raman microprobe spectra of minerals which may occur in alteration assemblages of epithermal deposits.

with these specialised techniques, the constituents of an assemblage are often difficult to uniquely identify owing to the mixing of the minerals at the microscope scale.

The laser Raman microprobe can provide more definitive data for resolving the constituents of such assemblages. Thus, albitic, potassic, and hematitic alteration styles, which may appear very similar in hand specimen, yield distinctive Raman spectra. Dark or opaque minerals (e.g., tourmaline, biotite, and bornite) tend to give weak but distinct spectra which still allow their proper identification.

Another advantage of Raman spectroscopy is that it can easily identify the various TiO_2 and other polymorphs. For example, anatase (Fig. 17) gives a very intense Raman spectrum, allowing even minute crystals to be readily detected. Preliminary studies of some Ordovician porphyry Cu–Au occurrences from New South Wales indicate that anatase and brookite are present in biotite alteration assemblages, in which these TiO_2 phases previously had been identified as rutile. Anatase is an indicator of low temperatures and possibly low fluid pH (Mathews 1976: American Mineralogist, 61, 419–424). We are now investigating how these TiO_2 polymorphs relate to depth of formation and to differences between high and low sulphur systems. The potential use of TiO_2 phases as indicators of porphyry environments is also currently being examined in resistate mineral studies (K. Scott, CSIRO Division of Exploration & Mining, personal communication 1996).

The laser Raman microprobe also facilitates rapid identification of more unusual minerals, such as zunyite (Fig. 17), which are characteristic of low-sulphur high-chlorine porphyry environments. The technique could be of particular importance in skarn environments where rapid identification of key accessory/indicator minerals is possible.

Epithermal mineralisation

Many minerals can be quickly identified by noting the frequency of the most intense band in the Raman spectrum. For example, most sulphates display an intense band near 1000 cm^{-1}; carbonates have an intense band near 1100 cm^{-1}; and feldspars have an intense band near 510 cm^{-1}. For other minerals, more than one band may be needed. Hence, sericite is characterised by bands near 100, 265, and 700 cm^{-1}, and the characteristic bands for sulphides occur below 500 cm^{-1}.

The identification of adularia is critical for distinguishing low-sulphidation systems; this mineral is one of the indicators of boiling. Since all adularia types have compositions close to pure orthoclase, the mineral is extremely difficult to identify by other analytical techniques (Dong & Morrison 1995: Mineralium Deposita, 30, 11–19). However, the structural disorder commonly present in adularia is reflected in its Raman spectrum, which has fewer peaks and broader bands than that of orthoclase (Fig. 18). Thus, Raman spectroscopy is a useful method for distinguishing between these two minerals, especially when the distinctive morphology of adularia is difficult to recognise.

Similarly, the laser Raman microprobe can also distinguish the various silica polymorphs (Kingma & Hemley 1994: American Mineralogist, 79, 269–273), making it potentially useful for determining the structural level of preservation of epithermal vein systems. Its ability to obtain spectra of both crystalline and non-crystalline materials might facilitate the recognition of thermal overprinting of veins in which the textures of epithermal and low-temperature quartz are visually preserved but the minerals are actually recrystallised.

Raman spectroscopy may be particularly useful in high-sulphidation epithermal systems, in which the friable and vuggy alteration assemblages near a mineral deposit pre-
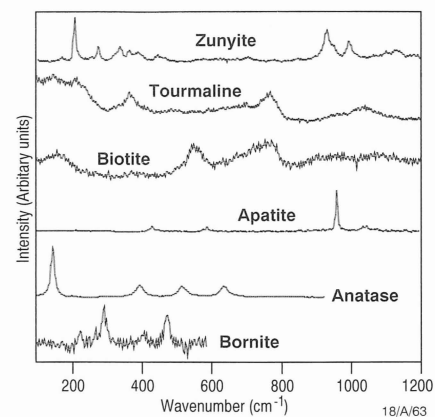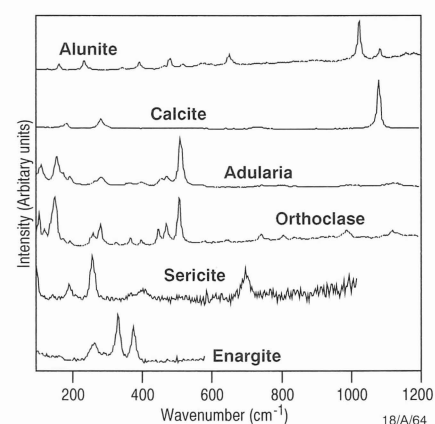
clude the preparation of good-quality thin sections. The laser Raman microprobe also provides a useful method for discriminating between key sulphide minerals (Mernagh & Trudu 1993: Chemical Geology, 103, 113–127), such as luzonite and enargite (Fig. 18), which are commonly zoned within these systems. Their identification would otherwise require the preparation of systematic polished thin-sections and/or geochemical analysis.

Comparisons with other techniques

In common with other spectroscopic techniques, Raman spectroscopy produces a spectral 'fingerprint' which can be used to identify each mineral. However, since it is a visible-light technique, fluorescent minerals or impurities in minerals may cause interference by producing sufficient fluorescence to swamp the weaker Raman signal. Using either a laser with a different wavelength or the complementary technique of infrared spectroscopy (the method used by the PIMA instruments) will generally overcome this problem. For example, PIMA can readily identify a number of clays which have strong fluorescence backgrounds in their Raman spectra. Be that as it may, PIMA does have its restrictions: it can detect only those minerals that contain water or OH and/or CO_3 groups, whereas the Raman microprobe can

identify a much larger range of minerals.

In theory, Raman spectra are similar to the infrared spectra produced by PIMA instruments, but the Raman bands are usually much sharper. The sharper Raman bands reduce the problem of overlapping bands (common in infrared spectroscopy) and make identification much easier. Both the Raman and PIMA instruments require little or no sample preparation and provide a rapid spectral analysis.

PIMA has the advantage of being portable and available for field use, whereas portable Raman spectrometers are still awaiting development. However, PIMA is designed to analyse a sample area of ~1 cm in diameter, which usually results in complex spectra representing mixtures of minerals; by contrast, the high spatial resolution (down to 1 µm) of the Raman microprobe allows each mineral to be identified separately.

The laser Raman microprobe is akin to a coarse sampling microprobe, but does not require a vacuum or a carbon-coated sample. Its ability to identify minerals *in situ* avoids the time-consuming sample preparation procedures associated with the preparation of thin sections or with analysis by X-ray fluorescence, X-ray diffraction, etc. Furthermore, X-ray methods may not detect minerals present in trace concentrations, but these may be readily identified using the Raman microprobe spot-analysis technique. Therefore, the laser Raman microprobe promises to be a very useful technique for the identification of minerals, not only in alteration assemblages but in samples from a wide variety of geological environments.

Acknowledgment

Complex attributes: new tools for enhancing aeromagnetic data

Peter J. Gunn[1], Desmond Fitzgerald[2], & Nabeel Yassi[2]

We have applied complex algebraic theory to develop several new methods for presenting aeromagnetic data. This note discusses the theory and possible applications of our 'complex attributes'.

The following mathematical description, which has been adapted from Taner et al. (1979: Geophysics, 44, 1041–1063), outlines how complex variable theory relates to profiles of magnetic (or any other) data.

A magnetic anomaly m(x) can be considered as the real part of a complex signal; thus:

$$M(x) = m(x) + j\, m^*(x)$$

where $m^*(x)$ is the imaginary (quadrature) component and M(x) is the complex signal, which is known as the analytic signal (cf. Roest et al. 1992: Geophysics, 57, 116–125).

$$|M(x)| = A(x) = [(m(x))^2 + (j\, m^*(x))^2]^{1/2}$$

where A(x) is the energy envelope which is the commonly used parameter in presentations of analytic signals in potential-fields studies.

$$\Phi(x) = \tan^{-1}[m^*(x)/m(x)]$$

where $\Phi(x)$ is called the instantaneous phase.

$$d\,\Phi(x)/dx = \omega(x)$$

where $\omega(x)$ is the instantaneous frequency.

Taner et al. described a convolution approach of using a Hilbert transform to calculate the quadrature component for profile data.
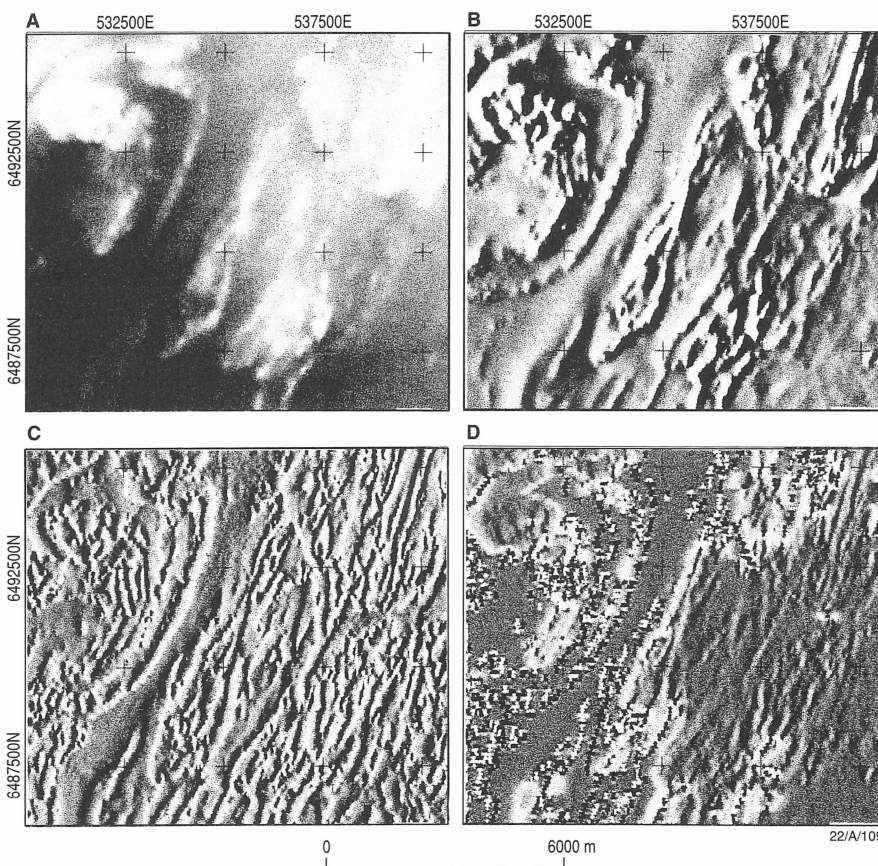
The complex attributes

The following examples of complex attributes are presented for profile data. Our reason for not initially using gridded aeromagnetic data is that profile aeromagnetic data has a much finer sample interval, and, as such, the results are not likely to be affected by problems caused by aliasing and interpolation. In previous studies in which we have calculated analytic signals, we have found that such effects can degrade the results for data sets in which the widths of anomalies are small relative to the flight-line spacing. We have selected a data set in which most of the magnetic features trend perpendicular to the flight lines, so that processing the profiles is likely to give results closely approximating a grid-based approach. Figure 19 presents our results.

We selected as our test data set (Fig. 19a) aeromagnetic data acquired on east–west flight lines spaced at 100 m and flown at a ground clearance of 60 m over the Broken Hill area of Australia. The sampling interval of the recording system was 7 m. The data were gridded to 20-m cells for display purposes, and presented as a straightforward image in which colour corresponds directly to amplitude. No sun-angle enhancement has been applied, although this would have increased the apparent detail in the data.

A **quadrature image** (Fig. 19b) of the same data set appears to show more detail than the original total magnetic intensity (TMI) image, perhaps because the quadrature data represent a 90° phase shift of the original

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Fig. 19. **Examples of images of complex attributes applied to a component of the magnetic field over the Broken Hill area. (A) Total magnetic intensity. (B) The quadrature (imaginary) field. (C) The instantaneous phase, which maps anomaly continuity and accurately locates magnetic sources. (D) The instantaneous frequency, which maps anomaly character.**