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Edited by
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Editor-in-Chief of Publications
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Foreword

The mineral industry in what used to be the British Empire has convened thirteen congresses from the first held in London in 1924 to this latest one in 1986. They were fairly evenly spaced, mostly at four-year intervals, except for a 19-year gap from 1930 to 1949. The Australasian Institute of Mining and Metallurgy was host and organiser for three of these congresses—in 1953, 1965, and now in 1986.

It is significant, as a sign of the times, that each one of these three congresses had a different name, although the numerical sequence was retained. In 1953 it was "Fifth Empire Mining and Metallurgical Congress"; in 1965 "Eighth Commonwealth Mining and Metallurgical Congress"; and in 1986 "13th Congress of the Council of Mining and Metallurgical Institutions". It is also significant that the venue of the 1986 Congress was changed to Singapore, on advice from the Council, from Australia and New Zealand where, according to custom, it had been expected to be held.

I have been involved officially in all three congresses hosted by The Aus.I.M.M.—as author, editor-in-chief, and deputy president respectively—and I am able to say that the political vicissitudes which gave rise to the above events, and the economic ones as well, have not made any perceptible difference to attitudes toward the congress, contributions to the technical sessions, or to the enthusiasm of participants.

Thus the 62-year history of these congresses, and my own personal observation over more than half this period, lead to the certain conclusion that in spite of the problems that sometimes seem to loom so large, there is a cohesion and fellowship among practitioners in the mineral industry which will ensure the continuation of these congresses far into the future. Indeed the very theme of this congress "The Twenty-First Century—Mining for Mankind" seems to support this conclusion as though it goes without saying, and perhaps also foreshadows an enlargement of the membership of the Council.

At any rate, the quality of the papers to be presented to this 13th Congress, and printed in these volumes, maintains the high standard which we have come to expect, and I would like to extend my congratulations to all contributors. I know, from first-hand experience, how much work there is in the editing and preparation for publication of technical works of this magnitude, and would like to thank those who gave so much of their time to ensure the excellence of these volumes.

Mr J. T. Woodcock	Volume 1	Guide to the Australian Mineral Industry
Mr D. A. Berkman	Volume 2	Geology and Exploration
Mr J. T. Brady Mr R. L. Kay Mr I. L. Hore-Lacy	Volume 3	Mining
Mr L. E. Fielding Mr A. R. Gordon	Volume 4	Metallurgy
Dr T. R. Scott Dr E. R. Segnit	Volume 5	General
Mr M. H. Jones Mr J. T. Woodcock	Volume 6	Plenary Addresses

Finally, I would like to thank the Editor-in-Chief, Mr J. T. Woodcock, and acknowledge the tremendous effort he always makes on behalf of The Institute.

Sir Russel Madigan, OBE
Chairman
Publications Committee

Editor's Preface

The papers on mineral resource geology, delivered at the 13th Congress of the Council of Mining and Metallurgical Institutions in May 1986, are presented in this volume. These contributions give some indication of the trends in technology and science in the minerals industry of the 21st century – which was the main objective of the Congress. They also demonstrate the striking diversity of scientific methods currently applied to geology and exploration in the mineral resources area.

About a quarter of the papers describe the use of computers in data manipulation for ore reserve estimates, for mine production planning, and in the enhancement of regional exploration data. Obviously computer assistance to exploration and mining geology is well established, and can be expected to increase in the future. Several systems of aerial definition of prospective localities, which are also expected to find increasing application, are described in the volume. These methods of remote sensing are complementary to regional geological studies, which with ore deposit modelling have also received some attention. As The Australasian Institute of Mining and Metallurgy is host to this Congress, it follows that the current regional exploration enthusiasms are indicated. Thus the search for gold deposits in Australasia receives considerable attention. Two new lead-zinc provinces of Mississippi Valley type in the north of Western Australia are described, and demonstrate the tenacity and competence of our base metal explorers.

The challenges which the 21st century will present to the minerals geoscience industry are currently somewhat obscure. With a lesser increase in world population and a slower growth in mineral consumption than predicted over the last few decades, and the existence of ample reserves of most minerals, there may be less incentive overall to seek new resources. Exploration for mineral deposits is expected to continue, but may increasingly focus on high grade or low cost orebodies, which will inevitably displace existing high cost operations.

Earth science and technology are shown by the papers in this volume to be rapidly expanding, and capable of further growth. Thus it may be confidently predicted that geoscience will meet the challenges of the 21st century – whatever they may be.

D. A. Berkman
Honorary Editor

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Computer enhancement of Landsat, magnetic, and other regional data

Kerry N. O'Sullivan[1]

ABSTRACT

The techniques originally developed to process digital images of Mars, later gained widespread acceptance when applied to Landsat data: they are now making a significant impact in fields of geology outside remote sensing. The three ingredients of success are seen to be firstly, the perceptual attributes of image displays and the use of colour; secondly, the absolute ability to register data from a variety of sources; and thirdly, the speed of specialist "interactive" digital image display systems. The future lies in further exploiting these attributes through a Geographic Information Systems (GIS) approach to data handling, integration and display.

INTRODUCTION

The basic techniques used to generate high quality images from digital data were originally developed for spacecraft images of Mars. However, the launch of ERTS-1 (later renamed Landsat-1) in 1972, unknowingly and unwittingly heralded the real beginnings of a new era in geological data handling as geologists, probably for the first time, encountered, and worked successfully with, continuous-tone images derived from extensive arrays of numbers. In the process of producing better Landsat "pictures" for improved photointerpretation they, almost fortuitously, discovered the full power of digital image array manipulation; a discovery made only newly accessible to the general public by the growing power and declining cost of computers and peripheral hardware. With hindsight, it is almost incidental that these early data were remotely sensed from space, as subsequent developments have shown how appropriate are image processing techniques to data from other sources.

The prime sensor system of the first three Landsat satellites, and one that is still extant alongside the Thematic Mapper (TM) of Landsat-5, is the 4-channel Multispectral Scanner System (MSS). This measures the integrated spectral radiances from contiguous 80 m ground cells within a 185 km swath. Viewed at scales appropriately small in relation to the ground cell, such data are amenable to conventional photointerpretation. In addition, the four separate spectral measurements obtained for every pixel allow of a large range of mathematical operations within and between the data arrays to produce specialized images.

The extreme interpretability of continous tone images is explained by the psychophysics of perception. Pattern and texture are attributes of the spatial domain easily interpreted by the eyes and brain. Colour hue, saturation and intensity are similarly familiar visual cues, as is that of stereoscopic acuity. These properties may be considered also as mutually exclusive dimensions of data display. Thus, if complementary aspects of a single data set, or separate aspects of multiple data sets are displayed using the above devices, not only is more information made available at one time, but in a form that should be easier to interpret.

FORMS OF DATA

CELL DATA

Cell data is the digital approximation of an analogue field, in which measurements occupy every cell of a two dimensional mesh, better described as lines and pixels. True cell data is acquired by scanners and imaging radar, but non-continous data can often be transformed into cells by a process known as gridding and interpolation.

POINT DATA

Point data are discrete measurements, for example, gravity readings. Such data have traditionally been displayed as intensity contour maps.

To generate contours, a grid or mesh is fitted over the distributed points, values are interpolated into the cells of the mesh, and lines of equal intensity are drawn. The resulting plan is a two-dimensional level slice; disrupting pattern and concealing subtlety. Gridding is a common precursor to machine contouring, and always affects the distribution of the data as a function of the interpolation algorithm used. The analyst should be aware of the characteristics and attributes of the more common gridding and resampling procedures.

A grid produced during contouring may be used as the lines and pixels of an image. When each cell is assigned a shade of grey proportional to its value it becomes a

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grey-scale image which maps intensity, and contains the visual cues of tone and texture. The line packing on a contour plan is proportional to the field gradient; therefore the result is effectively a mapping of slope. In contrast, an image is capable of preserving both large and small scale intensity features, and further can have both slope and intensity information displayed at the same time (Figure 5). An example in Guinness et al. (1983) is of a shaded-relief Bouguer gravity anomaly image covering midcontinental USA.

FLIGHT LINE DATA

Geophysical survey aircraft, flying a succession of parallel paths, generate flight line or profile data. Measurements made at given time intervals are representative of some physical parameter(s) of the earth beneath, usually of the gamma ray spectrum, total magnetic intensity, magnetic gradient, or various electrical properties. As with point data, line data can be turned into grid-arrays and treated as images. For an example of regional airborne magnetic data see Tucker et al. (1985), plus Figures 5 and 6.

GRAPHIC DATA

Graphic (or binary) data as points, lines and polygons complement image data. Examples are sample sites (points), faults (lines), and polygons (geological units); all of which are used with image displays to add supporting information (overlays). Polygons can also be used to restrict the area of specialized processing (masks).

DATA PROCESSING AND DISPLAY

A 4-band Landsat MSS scene contains about 30 Mb (megabyte = million numbers) of information; the 7-band Landsat TM about 230 Mb; and the 128-channel NASA Airborne Imaging Spectrometer approximately 1.28 Mb/km^2, or about 1 400 times the amount per unit area of the Landsat MSS.

To process and display such large data volumes it is necessary to have an adequate minicomputer, a large disc-storage capacity, a tape drive, and a specialised image display device. In industry, it is common to find a mini-computer of the VAX family or equivalent, disc capacity of between 400 and 1500 Mb, and a sophisticated image processing sub-system capable of displaying high resolution images in colour and monochrome on a TV monitor. The image processing unit is specially configured to hold a number of sub-images in its memory, and to execute a large range of operations on these almost instantaneously. Useful processing is also possible on machines as small as an IBM PC, but this is less efficient.

Equipment costs can range from A$50 000 to in excess of A$1 000 000. Ince (1983) describes the operation of digital image processing systems, and discusses trends and expected future developments.

Gridding point or line data may modify original values as a function of grid size, data distribution and the algorithm used. The larger the grid in relation to sample density, the greater the averaging.

The resampling that is involved in changing from an original grid size and/or orientation to another when, for example, registering different images, will variously affect the resultant scene geometry and pixel values. Three commonly used algorithms in order of increasing complexity are

1. nearest neighbour,
2. bilinear interpolation, and
3. cubic convolution.

The nearest neighbour algorithm is unique as no interpolation or smoothing takes place. A pixel in the output image is assigned the value of the nearest pixel in the input image, faithfully retaining all fine spatial detail. The result has a 'blocky' appearance with some distortion of the local geometry.

Bilinear interpolation selects a value for the output image by interpolating from the nearest four pixels in the original image, giving a slightly smoothed, but geometrically more accurate image compared to nearest neighbour.

Cubic convolution resampling makes use of the nearest sixteen pixels in the original image.

Assuming that data is in a gridded form, and that all the images being handled together have grids with a common origin, geometry and cell size, a number of categories of processing operations can be addressed. These are sometimes called

1. preprocessing (exclusive of gridding and resampling),
2. image enhancement,
3. classification, and
4. integration or merging.

PREPROCESSING

Preprocessing encompasses such procedures as destriping and geometric correction, some of which are mandatory, some of which are optional but desirable, and others of which may have been carried out on data prior to purchase. These are operations performed on gridded data before analysis. It is best first to remove residual defects from original line or point data prior to the gridding stage. This is part of data preparation rather than preprocessing, neither of which will be discussed further.

IMAGE ENHANCEMENT

Image enhancement covers all those processing operations concerned with making the image 'better' or more interpretable. Often, more than one rendering of the data is needed to explore fully all aspects, most especially when working with many channels or many types of data.

Image enhancement operations are of two types.

1. Point operations, which act upon the brightness values of individual pixels, for example ratios.
2. Neighbourhood operations which change pixel values as a function of the values of other pixels, for example spatial filters.

In point operations, digital numbers

(DN's) or pixel values are taken sequentially from a computer's storage device (usually magnetic tape or disc) and subjected to an arithmetic calculation which produces a new number. This number becomes the DN of the pixel in a derived image, which itself may become the input to subsequent operations.

To display a single image on a television screen, each pixel is assigned a shade of grey proportional to its signal intensity. Photographic copy may be generated directly by using a film-writing device, in which a modulated light source is passed across a sheet of unexposed photographic film, recording the image pixel-by-pixel and line-by-line. Copy of poorer quality can be made using electrostatic, ink-jet or ribbon plotters.

A colour television picture consists of three separate, but registered, black and white grey-scale images projected through red, green and blue guns. This fundamental 3-image construction of colour-composite displays should not be confused with the use of coloured graphics on single bands to 'paint' contour intervals or level slices; termed pseudocolour.

The image histogram is the basis on which all image enhancement operations are carried out; it is a plot of DN's versus frequency of their occurrence. The shape of the histogram and the spread of contained values assist in the selection of the most suitable types of enhancement.

The most commonly applied image enhancement utilities are as follows.

1. contrast stretches
    * linear
    * bi-linear
    * piecewise linear
    * equal area
    * various non-linear
2. ratios
3. principal components analysis
4. spatial filters

Morgan and Morris-Jones (1982) summarise some basic concepts in digital image processing.

Contrast stretching (Figure 1)

Many types of cosmetic enhancement are available to improve the contrast of an image. A linear stretch will space brightness values equally between black (DN 0) and white (usually = DN 255 = 2^8 levels = 8-bit range) to take full advantage of the displayable contrast range of the TV screen (or photographic film). The upper and lower thresholds for the stretch are selected by inspection of the image histogram. Three 8-bit black and white images together make a 24-bit (more than 16 million colours = 2^{24} levels) colour image. As a graph of input versus output values, the 'transfer function' for a linear stretch is a straight line similar to the D log H curve of photography.

Other contrast enhancement can be accomplished

1. by adjusting the slope and offset of the transfer function,
2. by modifying the transfer function to consist of more than one straight line section (bi-linear, piecewise linear), or
3. by applying a non-linear function.

Of the latter, a logarithmic function will improve contrast in dark areas more than the light, while an exponential function will do the reverse. A histogram equalisation stretch is useful in improving the contrast of very 'flat' images by preferentially stretching the most commonly occurring grey levels. A Gaussian stretch forces the image histogram to that of a Gaussian, bell-shaped, or normal distribution.

Contrast stretches are the basic working tools of the image analyst.

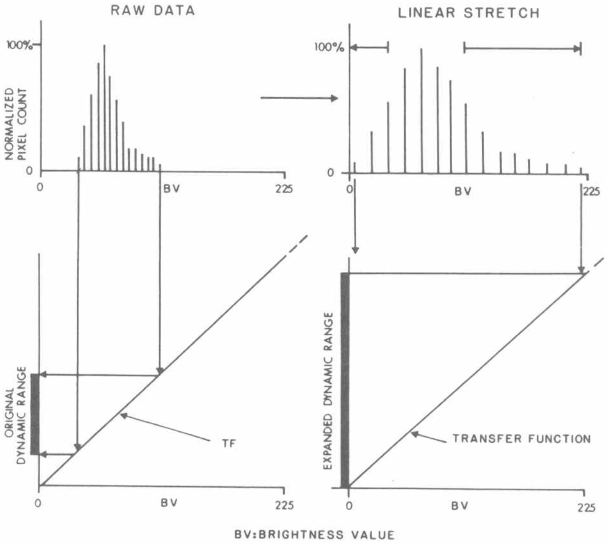

Fig. 1 **CONCEPT OF LINEAR CONTRAST ENHANCEMENT. (After Taranik, 1978)**

Ratios

To obtain a ratio image, the DN of each pixel in one band is divided by the DN of the corresponding pixel from another band to produce a DN for a pixel in a newly created third band. With spectral scanner data, the effect is to remove the varying illumination of the sun caused by topography (Figure 2), decrease the brightness (albedo) variation of the ground surface, and emphasise colour (spectral) differences between materials (Sabins, 1978). The radiance of one band is then portrayed relative to another, which, in the context of millions of scene pixels, produces a spatial mapping of relative spectral absorptions. Landsat MSS band ratios have been used to map surface iron oxides by exploiting the presence of a ferric iron absorption feature close to 0.9 µm wavelength on the assumption that limonite is more important than sulphides in defining the relevant remotely sensed physical properties of many sulphide mineral deposits. In arid terrains the Landsat MSS ratios 4/5, 5/6, and 6/7 have been used in this way by Rowan et al. (1976) in Nevada, Raines et al. (1978) in Wyoming, and Podwysocki and Segal (1980) in Utah. Only Raines (1980) claims limited success in the Australian weathering environment. Other workers have used spectral ratios to assist in the mapping of lithologies: for example, in Saudi Arabia, Blodget et al. (1978) and Brown and Blodget (1982); in Oman, Rothery and Milton (1981).

Segal (1983) gives a good review of previous research into the use of ratios for limonite mapping, and suggests an alternative composite ratio of channels to overcome the effect of vegetation.

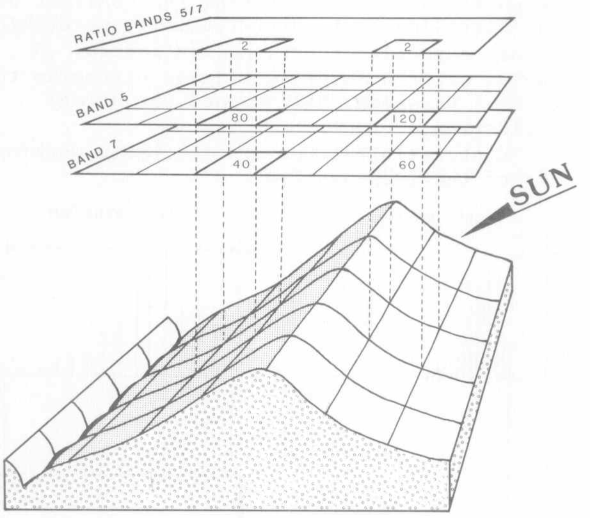

Fig. 2 **LANDSAT BAND RATIOS**

Ratios are used in the processing of data from advanced aircraft and satellite scanners to exploit reflectance minima; particularly those absorptions centred around 2.2 µm wavelength that are characteristic of hydroxyl bearing minerals (clays) and carbonates. The Landsat TM has 7 channels, while 10-15 channels are common on aircraft systems. The geologist must take advantage of the more detailed spectral information, yet at the same time is constrained in colour image display by a maximum of three contributory channels. Chavez et al. (1982) present a statistical method for selecting those Landsat MSS ratios with the highest information content. Sheffield (1985) offers another statistical method for selecting from many channels the three that together contain the most significant variance when used to make a colour composite image. Kahle (1980) notes how, in a particular instance, ratios are unsuited for the type of spectral discrimination required; hence, band ratios are not always the optimum processing method, and carry the additional restrictions of

1. emphasizing random noise, and
2. removing surface brightness effects which can, in some instances, remove the very parameter by which the analyst discriminates materials: two rocks can have similar spectra but different albedos.

Principal Components Analysis (PCA)

The PCA method is frequently applied to multi-channel spectral data in order to enhance subtle differences between materials, accomplished in part through a compression of most of the variance from a large number of original channels into a smaller number of transformed ones. This is best illustrated with two spectral bands. If the DN's of pixels in one band are plotted against those of the other, a scattergram of covariance is produced. The scatter of points usually takes on the shape of an ellipse whose major and minor axes better describe the variation of the data than did the original ones. These new axes, or principal components (PC's), are referred to as PC1 and PC2 respectively, and are used to derive transformed values for the image pixels. These values are used in new images. Geometrically, the operation is a rotation and translation of the original band axes (Figure 3).

Where more than three channels are present, more than three axes will be found within a 'hyperellipsoid' in 'hyperspace'. The four channels of the Landsat MSS produce PC's 1-4 where, typically, PC1 may contain about 85% of the four-channel variance, PC2 about 10%, and PC's 3 and 4 the remaining few percent, much of which is noise. The use of the first three PC's in a colour composite Landsat image will often account for more than 99% of scene variance (Lillesand and Kiefer, 1979).

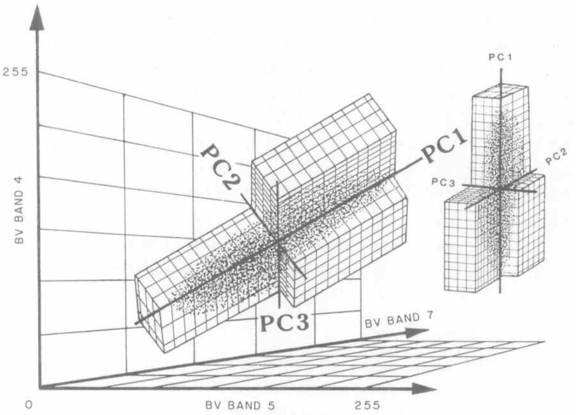

Fig. 3 **PRINCIPAL COMPONENTS ANALYSIS**

For Landsat MSS data, PC1 equates with average scene brightness (albedo); PC2 with spectral content; and PC3 and PC4 essentially with noise. It is thus a means of data compression for more efficient display and interpretation. Blodget et al. (1978) have applied PCA to the discrimination of rock classes and hydrothermal alteration products in Saudi Arabia.

The use of PC's introduces the problem of feature hues being unrelated to colour keys derived from experience. For example, vegetation is unlikely to be red in the PC composite of a Landsat MSS image. The analyst cannot, as with ratios, model mentally the spectral implications of colours that are determined by scene statistics. Inverse PCA, sometimes known as a 'decorrelation stretch' partly overcomes this problem. Kahle and co-workers (1980) achieved excellent results in displaying subtle spectral differences that were being masked by topographically controlled surface temperature in thermal infrared data from the E. Tintic Mountains of Utah.

Inverse PCA is a three step procedure involving

1. a PC transformation to decorrelate the input data,
2. normalisation of the data to a Gaussian distribution of specified variance to occupy the majority of the available

colour space, and
3. inversion of the initial PC transformation to return to the original co-ordinate orientation.

Together, these have the effect of returning to hues similar to those in a conventional colour composite of the same bands, but with more colour saturation. Kahle and Goetz (1983) and, using this technique, Gillespie et al. (1984) describe the exploitation of mineral signature information in the 8-12 µm wavelength region for areas of Death Valley, California.

Spatial Filtering

All enhancements so far discussed have operated to modify the DN of an individual pixel, better to display some facet of recorded spectral data. To the human observer, however, the colour of the world around is often of lesser practical significance than the spatial component, as can be demonstrated by a simple comparison of colour and monochrome television transmissions. Similarly, the pattern, tone and texture of a Landsat image generally provides more information than does the colour. Hence an ability to work within the spatial domain promises a very rich reward.

Digital image filtering is used not only in image enhancement, but also within a much wider field of signal processing, examples of which include the suppression of noise, the correction of radiance effects, and the recognition of pattern. Only enhancement will be considered here.

The spatial component of an image can be defined as the brightness change over distance, and as such is best described as a wave-form. Viewed in cross section, a mountain would appear as a long-wavelength feature, on which was superimposed the shorter-wavelength (or high frequency) sub-features derived from valleys and ridges.

In images, the format of an extensive array of rows and pixels means that intensity profiles can be constructed in any direction, hence an image is also a complex map of spatial change, consisting of a whole spectrum of spatial frequencies. These frequency distributions are best analysed in the frequency domain using Fourier analysis, but can more simply be handled in the spatial domain by convolution filtering.

Convolution filtering requires that a neighbourhood-box or pixel-array be moved incrementally across and down an image, pixel-by-pixel, and line-by-line. At each position a mathematical operation is carried out to derive a modified value for the current central pixel, the brightness of which is thus changed as a function of the neighbourhood pixels. Most commonly the number of pixels in the box is odd, and the box shape is square. The operation is called filtering because of its ability to pass, block or modify selected spatial frequencies.

Examples of some filters are
1. low frequency (low pass),
2. high frequency (high pass),
3. edge-enhancement,
4. variance,
5. aspect, and
6. slope.

The low frequency filter (Figure 4), at its simplest, is a moving mean in which the central pixel is replaced with the average of all pixels in the box. This smoothing filter can be used to reduce speckle in an image, or as the first step in both high-frequency filtering and edge-enhancement.

A high frequency filter (Figure 4) passes only the high spatial frequencies by subtracting the previous low-pass image from the original. Such a filter is variously used in remote sensing to sharpen the appearance of such features as stratigraphic boundaries, faults, and rock fractures. It can remove regional effects on certain types of geophysical data; for example total magnetic intensity.

An edge-enhancement filter (Figure 4) subtracts the average value of a moving box from the original value of the central pixel to produce an edge component of high frequency. This is added back into the original image with the effect of emphasizing boundaries.

A variance filter calculates the variance (spread of values about the mean) of pixels in a box. Such an image generally proves difficult to interpret, but is a measure of texture.

An aspect filter fits a surface across the pixels in a box, replacing the central pixel with a value related to the aspect of

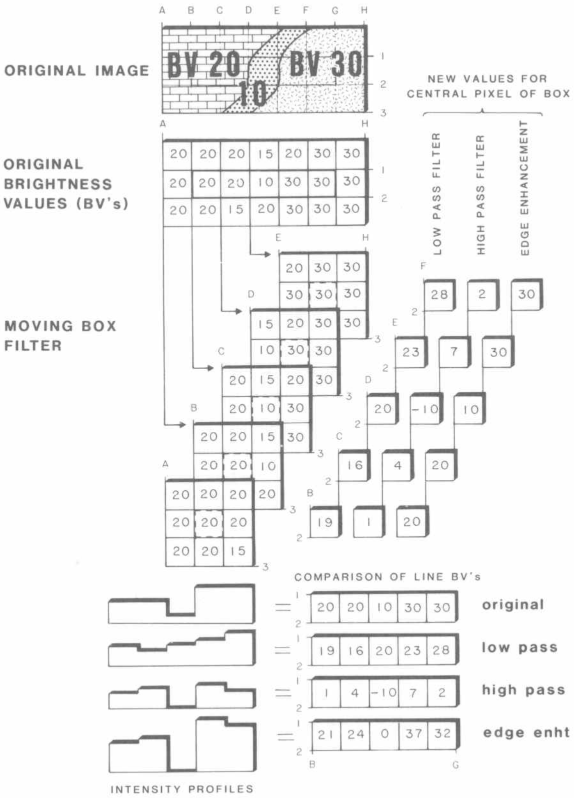

Fig. 4 **SPATIAL FILTERS**

LOW PASS: average all pixels in box

HIGH PASS: subtract low-pass from original BV

EDGE ENHT.: add high-pass to original BV

that surface. This may take the form of a grey-scale range from white to black through the 360 degrees of possible facings. Such filters are useful in studies involving terrain elevation data, magnetic intensity and gravity.

A slope filter will calculate the slope or gradient within a box and replace the central pixel according to a scale similar to that of the aspect filter. Such images can be useful when derived from terrain elevation, magnetic intensity, gravity, and to a certain extent, geochemical data.

In all the above, the size of the local area is selected by the analyst; the larger the box size, the more regional (or conversely the less local) is the effect of the filter. With many of the filters it is possible to 'add back' any desired percentage of the original image, giving the analyst a very large range of degrees of spatial enhancement from which to choose.

Other, and more specialized filters exist that are not necessarily equant in dimensions. Some of the more useful generate what are variously described as shaded relief images, shadowgrams, gradient images and synthetic relief images; all of which give the appearance of shining a simulated light source across a surface. Moore and Simpson (1982) show terrain elevation images of the Australian continent, and Broome et al. (1985) present examples of total magnetic intensity images from Canada.

CLASSIFICATION

Classification is the process of assigning individual pixels of an image to classes. Threshold values for each class are usually extracted from the statistics of a control group of pixels known as a 'training set'. Spectral classification can give excellent results on the homogeneous targets of planted crops. The complex mixtures of rock, soil and vegetation encountered in nature have rendered applications to geology of limited use. However, the increasing sophistication and resolution of data, the better understanding of the physical properties of the Earth, and the development of more advanced algorithms, may lead to a more effective use of classification techniques in the future.

Some useful results have been achieved by Taranik et al. (1978) in searching for nickeliferous laterite in Indonesia; by Schmidt (1980) seeking to identify large porphyry copper systems in Pakistan; and by Baker and Baldwin (1981) in locating gossans in the porphyry copper belt of Chile. More recently, Realmuto (1984) applied supervised classification algorithms to airborne TM data over areas of phyllic alteration in the vicinity of the Dos Pobres and Safford porphyry copper deposits in Arizona, with encouraging results.

DATA INTEGRATION AND MERGING

If ways can be found to combine a number of different sets of information into a single interpretable display, and at the same time retain the essential attributes of each, the task of the analyst is eased because the dimensionality of the data is reduced. The use of both ratios and PCA methods are moves to this end.

Methods that rely heavily on human perception are

1. graphic overlays,
2. three-layer colour composites,
3. stereoscopic image pairs,
4. colour space enhancements, and
5. perspective and 3-D views.

Graphic overlays consist of points, lines and polygons placed on top of image data, using colours selected from a limited palette. Overlain data can depict such items as mineral occurrences, faults, geological boundaries, geophysical or terrain contours, and sample locations. Advantages include simplicity of display and easy identification of information components.

Three-layer composites have been discussed where they relate to television colour images. The process is a form of data merging that preserves intensity information from separate channels while expressing correlations in terms of colour. Such composites are limited to the use of three variables by the necessity for assignment to three primary colours, and are successful when firstly, the spatial resolution of each channel is well matched and secondly, the channels are all derived from related fields. Richards et al. (1983), Nevitt and Barr (1985), and Smith (1985), all contain examples of airborne gamma ray spectrometry handled in this way. The reduction of such data to ground level concentrations of the three main naturally occurring radioelements of potassium, uranium and thorium (Grasty, 1976) effectively provides geochemical maps of the distribution of these three elements, and supplies a lithological mapping capability insofar as the three elements vary systematically with rock type. No other method is as suitable for displaying point-source data, and can truly be said to have revolutionised the geological use of gamma ray spectrometry. Duval (1981), using similar data, has explored more widely the use of colour composite ratio images.

When data sets are not compatible (see Green, 1984) the resulting colour patterns may be confusing, and not clearly attributable to any sensible interrelationship of the three variables.

Stereoscopic image pairs enable the analyst to observe a third dimension, and can be generated from any digital image or combination of images. A new image (stereo mate) is created by laterally shifting each pixel by an amount proportional to the original brightness; introducing parallax proportional to intensity. Such a pixel shift is equally effective with non-terrain data such as total magnetic intensity (Colvocoresses, 1979; Green, 1980; Hastings, 1983). It is thus possible to combine up to four channels of data in this way, three using the colour gamut, and one the third dimension.

Broome et al. (1985) illustrate with airborne magnetic data the anaglyph method of stereoscopic display in which the original and shifted images are overprinted in separate colours. The image is viewed through glasses containing a filter lens of each colour.

Colour-space enhancements are made more complex by the non linear response of the eye to changes in colour. A useful introduction to colour perception is included in Smith and Anson (eds.) 1968.

Colour can be described mathematically in terms of the three nearly independent perceptual variables of hue, saturation, and intensity (Buchanan, 1979; Gillespie, 1980) where hues (H) represent the range of pure colours, saturation (S) the dilution of those hues with white light, and intensity (I) the overall brightness level between the extremes of purest black and white. The HSI method of handling colour is, for many purposes, better than the tristimulus system of red, blue and green (Raines, 1977). Using a photographic approximation of an HSI transformation, Harris and Graham (1976) combined spectral information from Landsat data with spatial information from airborne side-looking radar for the first time. The intensity of the radar channel was used to modulate the colour of the Landsat three-band colour image. Four channels of data were thus combined in a way that made the perception of data loss caused by the fourth channel very small.

Kruse and Raines (1984) describe how a transformation into HSI space of an image that has already been well contrast stretched will allow colour saturation to be considerably increased without changing the hue. This acts by reducing the correlation between bands, and is similar to the decorrelation stretch based on principal components transforms: it does not selectively enhance noise in the same way. Using test sites in New Mexico, Kruse (1984) shows how an HSI enhancement, in quantifying colour variation in colour ratio composites, can be used to simplify image analysis and reduce interpreter bias.

THE WAY FORWARD

The physical keys to mineral discovery lie not exclusively with any one set of physical measurements, but rather with all information taken together and focussed through the boots of a field geologist. Much remotely sensed data is new and will contribute increasingly to the understanding of the mineralogy, chemistry and structure of the Earth, but will always be used in conjunction with ancillary information. It is logical therefore, having developed the image handling and interpretational skills for individual data sets, to then develop the more complex skills and tools for manipulating images through a data base consisting of large spatial arrays. In this way the perceptual skills of the brain will be fully utilised in the analysis of images, which themselves are capable of interrogation and interactive change at the behest of the interpreter.

At the simplest level of merging, Short (1982) explains in some detail how high spatial resolution (30 m) data from a panchromatic imaging device can be merged with spectral information from the lower resolution Landsat MSS using a process known as normalisation. This retains both the high resolution boundary information and textures of the panchromatic image, with colour from the MSS.

O'Callaghan and O'Sullivan (1982) outline the structure of an image-based GIS developed for the Broken Hill area of New South Wales, which concentrates on the handling of Landsat, topographic and geophysical data.

Green and Craig (1984) draw attention to the unrealised potential of integrated image data-bases, and explore the application of models based on the increments of new information from each data set, rather than the rarely successful multivariate classification.

Bolivar et al. (1983) give examples of the integration of reconnaissance scale data over part of the State of Colorado. The data include Landsat, stream sediment geochemistry, airborne geophysics, mineral occurrences and geological maps. The authors state that sophisticated statistical routines are not necessary for initial interpretation; both obvious and subtle correlations between integrated data sets can be identified quickly and simply in images.

Other moves towards the development of geological image data-bases are reported by Hastings (1983), Eliason et al. (1983), Dwyer et al. (1984), and Conradsen et al. (1984). Aarnisalo et al. (1982), and Aarnisalo (1984) have taken some of the most significant and practical steps in the integration of Landsat, geophysics, geochemistry and topographic data in the glaciated Precambrian Shield of Finland, as part of a search for Mo, Cu-Zn, Ni, Ni-Cu and Outokumpu-type Cu-Co-Zn ores.

Figures 6 and 7 are examples of more advanced merging techniques.

Future trends are clearly towards more data, better data, powerful processing systems, appropriate display and hard-copy devices, the integration of information, and the direct involvement of the field geologist in interpretation. It is also to be expected that machines of a somewhat limited image processing capability will, within a few years, be commonplace in medium sized field offices, to complement the central processing facilities already present within major exploration companies.

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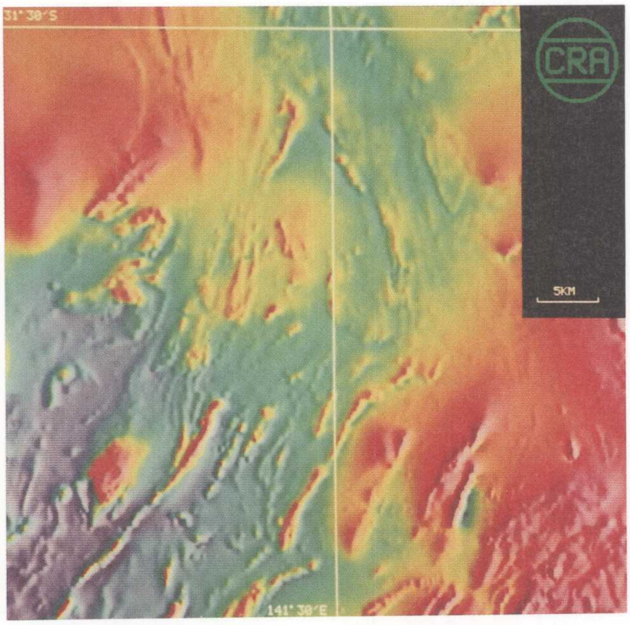

Fig. 5: COMBINED MAGNETIC[1] SLOPE AND INTENSITY: BROKEN HILL, N.S.W.
Pseudo-relief = magnetic slope.
Colours = total magnetic intensity (blue = low, red = high).

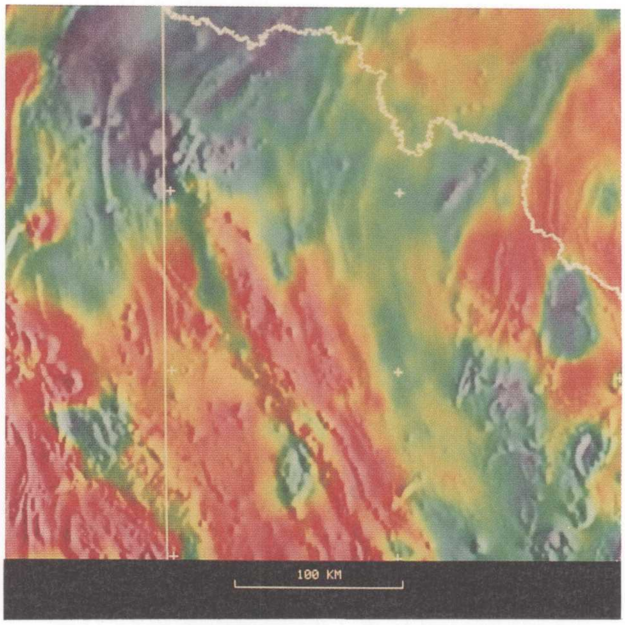

Fig. 6: COMBINED GRAVITY[1] AND MAGNETICS[1]: EASTERN MURRAY BASIN (SA, NSW, VIC)
Pseudo-relief = magnetic slope.
Colours = bouguer gravity (blue = low, red = high).

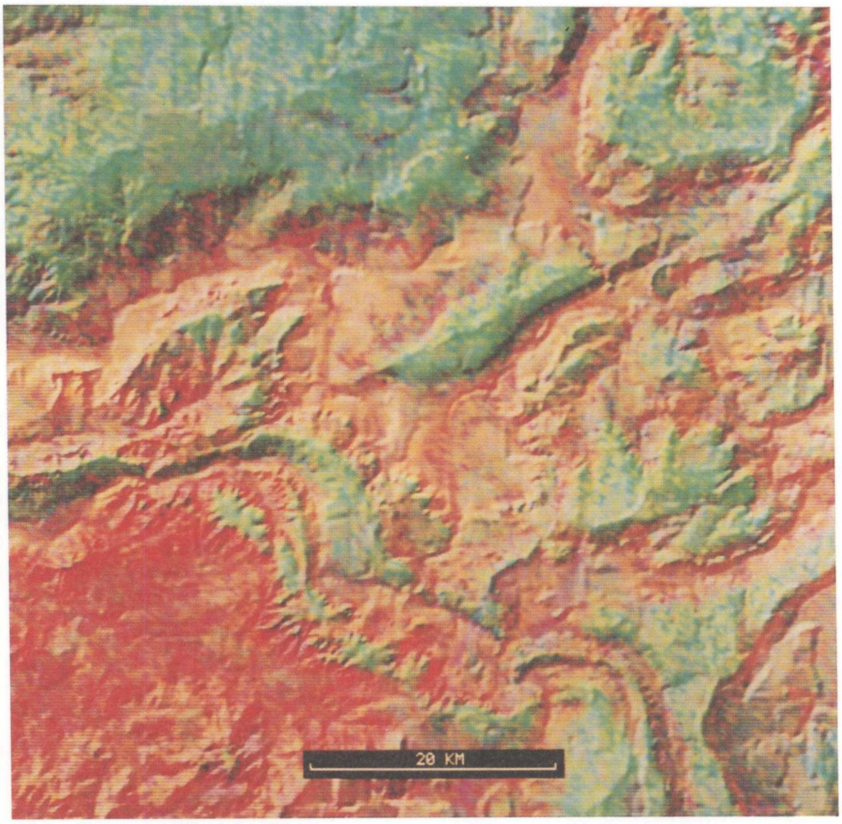

Fig. 7: COMBINED TERRAIN ELEVATION AND GAMMA RAY SPECTROMETRY
Pseudo-relief = terrain slope. Colours = gamma ray spectrometry with U on the blue gun, Th on green, and K on red.

[1] Digital data source: Bureau of Mineral Resources.

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