Three-Dimensional Integration of Remotely Sensed Geological Data: A Methodology for Petroleum Exploration*

Abstract

The standard approach to integration of satellite imagery and sub-surface geological data has been the comparison of a map-view image interpretation with a selection of sub-surface cross-sections. The relationship between surface and subsurface geology can be better understood through quantitative three-dimensional (3D) computer modeling. This study tests techniques to integrate a 3D digital terrain model with 3D sub-surface interpretations. Data types integrated, from a portion of the Paradox Basin, southeast Utah, include Landsat TM imagery, digital elevation data (DEM), and sub-surface gravity and magnetic data. Combined modeling of basement and topographic features suggests the traditional lineament analysis approach to structural interpretation is over-simplistic. Integration of DEM and image data displayed in 3D proved more effective for lithology discrimination than a map-view approach. Automated strike and dip interpretation algorithms require DEM data at resolutions better than 70 m by 90 m. The methodology tested is beneficial to interpretation of imagery data in frontier exploration areas.

Introduction

Integration of remote sensing and digital terrain modeling has been demonstrated to produce significant gains, and it is a well-established technique in areas such as environmental impact assessment (Baker, 1991), landslide hazard assessment (Huang and Chen, 1991), and surface mineral exploration (Braux *et al.*, 1990). Software has been developed that combines image data with digital elevation models (DEM) and produces three-dimensional surface displays with perspective viewing (e.g., Duguay *et al.*, 1989; McGuffie *et al.*, 1989; Morris, 1991). In addition, the value of integrating remote sensing with geographic information systems (GIS) has been demonstrated and software packages are available (e.g., Bultman and Getting, 1991; Runsheng *et al.*, 1991).

However, in the field of trying to deduce sub-surface geology from satellite imagery, three-dimensional (3D) modeling techniques, beyond the display of a single surface in perspective, have not been fully employed in an integrated fashion. The standard approach to combining sub-surface data with image interpretation has been the comparison of a map-view (2D) image interpretation with a selection of sub-surface cross-sections. The resulting synthesis would be described through a series of non-quantitative, idealized, 3D block diagrams. But this approach does not get the most information out of the data, and may result in unrealistic modeling of geological features such as fault geometries and lithologic boundaries.

This study tests techniques to integrate a 3D digital terrain model with 3D subsurface interpretations in order to construct quantitative models of the geology. In particular, it aims to demonstrate methods that will be beneficial in interpretation of imagery data in frontier exploration areas where few sub-surface data are available. The key objectives are

- To gain a better understanding of the relationship between subsurface geology and surface geology as interpreted from satellite imagery; and
- To test if, and by how much, the three-dimensional methods developed in this study facilitate the understanding of subsurface geology.

This study is multi-disciplinary in the sense that it incorporates concepts and methods from the fields of remote sensing, geographic information systems, subsurface geology, digital terrain modeling, computer mapping, and three-dimensional modeling to establish a methodology to maximize the interpretation of the geological information.

Study Area

The Blanding sub-basin of the Paradox Basin in southeast Utah was selected to test the methodology as it is a proven hydrocarbon province with plentiful subsurface data and good surface exposures. The setting and a summary of the regional structural features are shown in Figure 1. Structural relief on Mesozoic reference horizons is approximately 6,000 feet from the base of the Blanding Basin to the crest of the Monument Upwarp.

The Paradox Basin was formed during Pennsylvanian time as a transtensional basin, with the main deformation occurring along northwest- to southeast-trending fault zones, seen in surface imagery as prominent lineaments such as the Nequoia-Abajo Lineament (Knepper, 1982; Stevenson and Baars, 1986). This pattern is complicated by a perpendicular series of regional lineament zones trending northeast to southwest. Within the study area are three major lineaments (Figure 1). The Four Corners Lineament, trending NW-SE, defines the southern limits of the Paradox Basin, and is a strike-slip fault with right-lateral displacement. The NE-SW-trending Coconino Lineament is interpreted by Davis (1978) as a major partitioning element in the basement extending beyond the Paradox Basin. The Monument Upwarp and Comb Ridge Monocline are features along the Coconino Li-

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*Presented at the Ninth Thematic Conference on Geologic Remote Sensing, Pasadena, California, 8-11 February 1993.

Photogrammetric Engineering & Remote Sensing,
Vol. 59, No. 8, August 1993, pp. 1251–1256.

0099-1112/93/5908–1251$03.00/0

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neament. The House Creek fault zone consists of several NE-SW-trending *en echelon* faults that suggest left-lateral movement (Stevenson and Baars, 1986), which is compatible with these being antithetic shear faults to the NW-SE-trending fault zones. A deep-seated fault underlying the Comb Ridge monocline lies *en echelon* to the House Creek fault zone (Stevenson and Baars, 1986). During Laramide time (Late Cretaceous to Early Eocene), the Colorado Plateau was subjected to compressional forces, and large-scale inversion structures, such as the broad upwarps and monoclines, were developed (Blakey and Gubitosa, 1984; Peterson, 1986; Blakey, 1988).

The area of interest is between 110° to 109° longitude and 37° to 38° latitude North, in southeast Utah. Pennsylvanian and Permian age rocks are exposed on the Monument Upwarp (Figures 2 and 3). Late Permian and early Jurassic rocks are exposed in Comb Wash. The Jurassic-age Wingate, Kayenta, and Navajo formations are exposed on Comb Ridge. A major surface topographic feature, on the eastern boundary of Comb Ridge, is the Abajo Mountains which are formed by Oligocene laccolithic intrusions. East of Comb Ridge are younger Jurassic and Early Cretaceous units exposed in river valleys and on the mesa cliffs. Major drainages within the study area include the San Juan River that tracks across the southern portion from east to west. As the San Juan crosses Comb Ridge and the Monument Upwarp, there is a classic goose-neck incised meander-loop pattern associated with antecedence. Major north-south drainages include Montezuma Creek, Recapture Creek, Cottonwood Wash, and Comb Wash (Figure 3). South of the San Juan River, surface exposures of Jurassic Morrison Formation to Navajo Sandstone are masked by Recent aeolian deposits.

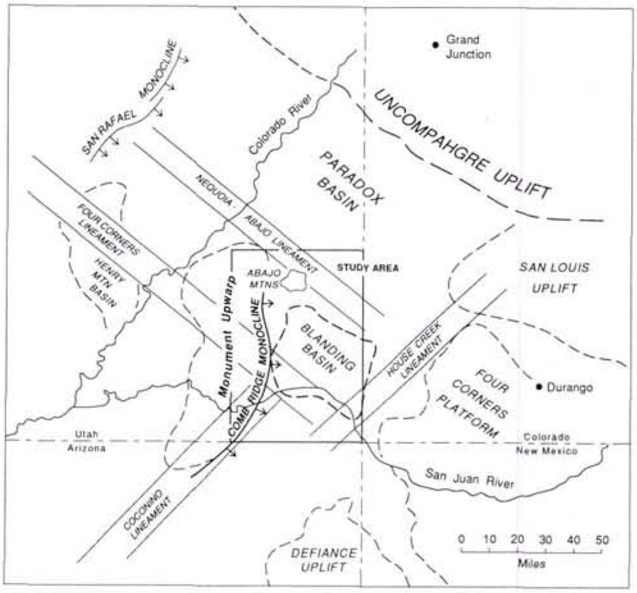


Figure 1. Location map showing regional structural features and study area (after Stevenson and Baars, 1986).

Methods

Data Set

A seven-band Landsat Thematic Mapper (TM) image in digital format was used in this study for lithologic discrimination. Two images were tested: a three-band decorrelated principal components (PC) image (bands 1,4,5,7 with PC 1,2,3 displayed in Red, Green, Blue (RGB), respectively), and a stretched false-color composite (bands 1,4,5 displayed in RGB, respectively). The stretched false-color composite image was the most useful in regional lithological interpretations. The noise introduced in the PC image by the equal weighting of decreasing PCs was accentuated when the image was resampled to larger pixels, negating any spectral enhancement that this method produced at full resolution.

Digital elevation data for this study were obtained from the USGS 1-degree digital data set (1° DEM data are used to map at a scale of 1:250,000). These data have a pixel resolution of 70 by 90 metres with a vertical accuracy of 30 m and a horizontal accuracy of 130 m. The gravity and magnetic interpretations are from Case and Joesting (1972). The interpreted depth to basement was digitized from the map (1:250,000); the locations of interpreted basement faults were digitized as a separate file.

Data Processing Procedure

The processing stages are outlined in Figure 4. The first stage includes the digital image processing of Landsat TM Imagery to enhance the surface geology interpretation. The enhanced image was combined with digital elevation data (DEM) to produce a digital terrain model (DTM) to further improve the interpretation of the surface geology. The DEM data were compared with the gravity and magnetic interpretations using two-dimensional GIS overlay techniques and three-dimensional surface comparison methods to identify the relationship between surface topography and sub-surface basement structures. The co-registered image and DEM data were used to test the usefulness of automatic strike and dip, using software developed by researchers at the University College, University of London. Finally, the RAINDROP software developed by Morris (1991) was run on the DEM data to identify major drainages.

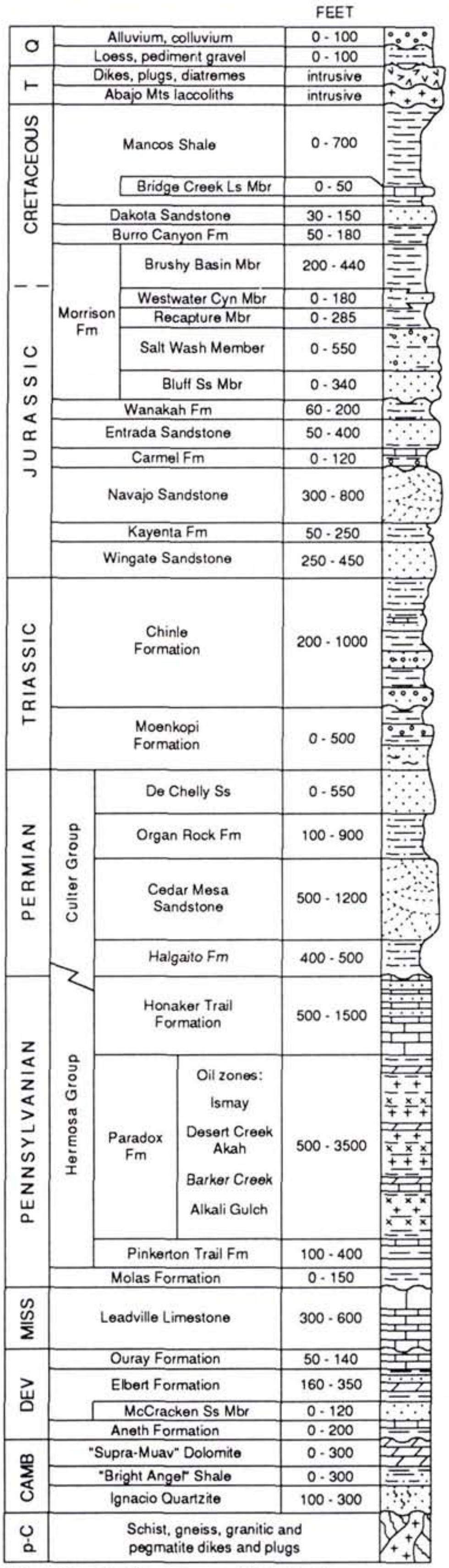
To test the proposed methodology, three commercially available software packages are linked: Image Processing System from Erdas, CPS3 mapping package from Radian Inc., and the Stratigraphic Geocellular Modelling (SGM) Package from Stratamodel Inc. The Erdas System used in this study is a personal-computer version mounted on a Compaq 386 under DOS. The CPS3 and SGM software run on a Silicon Graphics IRIS Unix workstation. Network software was used to translate files between DOS and Unix formats.

Results

Structural Interpretation

The methods that are traditionally used for lineament analysis in remote sensing are summarized by Drury (1987). The standard technique includes an initial stage of image processing using high-pass and directional filters that detect edges with preferred orientations, followed by visual interpretation of lineaments with a classification scheme based on the degree of confidence. In some studies, the strike of interpreted lineaments are plotted on a rose diagram to gain an understanding of trends in the regional structural fabric. This approach has been successfully automated (Saether *et al.*, 1991).

The ability of this technique to distinguish between surface lineaments that represent geology and those of man-made origin varies considerably (Saether *et al.*, 1991; Baumgardner, 1991). Factors that control the accuracy include the



System	Group	Formation	Member	FEET
Q		Alluvium, colluvium		0 - 100
Q		Loess, pediment gravel		0 - 100
T		Dikes, plugs, diatremes		intrusive
T		Abajo Mts laccoliths		intrusive
CRETACEOUS		Mancos Shale		0 - 700
			Bridge Creek Ls Mbr	0 - 50
		Dakota Sandstone		30 - 150
		Burro Canyon Fm		50 - 180
JURASSIC		Morrison Fm	Brushy Basin Mbr	200 - 440
			Westwater Cyn Mbr	0 - 180
			Recapture Mbr	0 - 285
			Salt Wash Member	0 - 550
			Bluff Ss Mbr	0 - 340
		Wanakah Fm		60 - 200
		Entrada Sandstone		50 - 400
		Carmel Fm		0 - 120
		Navajo Sandstone		300 - 800
		Kayenta Fm		50 - 250
		Wingate Sandstone		250 - 450
TRIASSIC		Chinle Formation		200 - 1000
		Moenkopi Formation		0 - 500
PERMIAN	Culter Group	De Chelly Ss		0 - 550
		Organ Rock Fm		100 - 900
		Cedar Mesa Sandstone		500 - 1200
		Halgaito Fm		400 - 500
PENNSYLVANIAN	Hermosa Group	Honaker Trail Formation		500 - 1500
		Paradox Fm	Oil zones: Ismay Desert Creek Akah Barker Creek Alkali Gulch	500 - 3500
		Pinkerton Trail Fm		100 - 400
		Molas Formation		0 - 150
MISS		Leadville Limestone		300 - 600
DEV		Ouray Formation		50 - 140
		Elbert Formation		160 - 350
			McCracken Ss Mbr	0 - 120
		Aneth Formation		0 - 200
CAMB		"Supra-Muav" Dolomite		0 - 300
		"Bright Angel" Shale		0 - 300
		Ignacio Quartzite		100 - 300
p-C		Schist, gneiss, granitic and pegmatite dikes and plugs		

Figure 2. Stratigraphy and lithologies exposed in the study area (after Hintze, 1988).

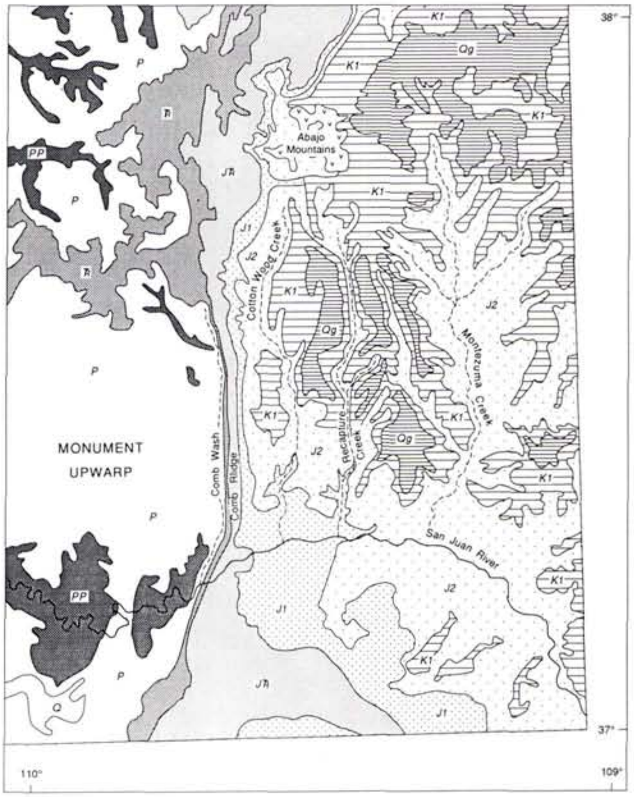


Figure 3. Geological map of the study area (after USGS geological maps 1:1,000,000). PP= Pennsylvanian; P= Permian; Tr= Triassic; JTr= Triassic-Jurassic; J1= Middle Jurassic; J2= Upper Jurassic; K1= Lower Cretaceous; Qg= Quaternary, Q= Quaternary.

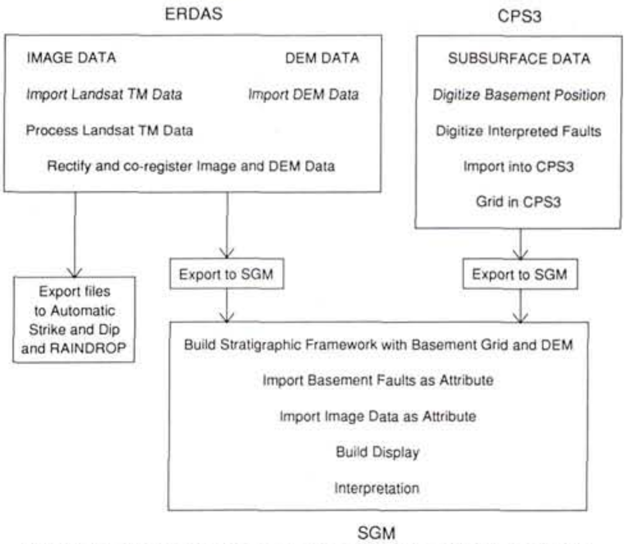


Figure 4. Data processing procedure used in this study.

Figure 5. Two-dimensional display in Erdas of DEM data in gray-scale and basement faults overlay (white lines).

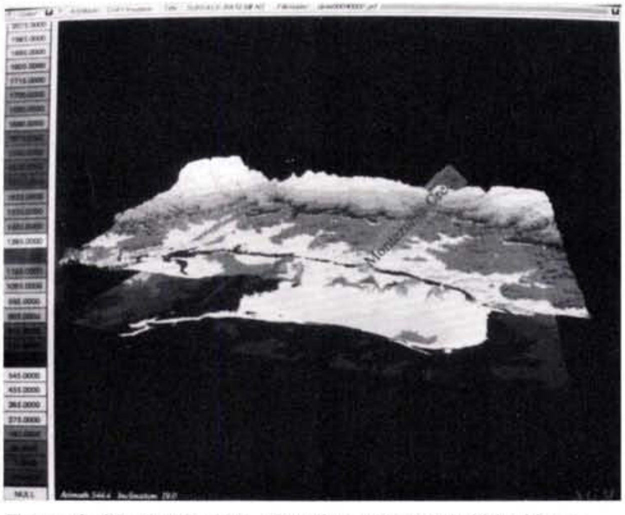


Figure 6. Display in SGM of surface DEM and grid of basement. Note the location of Montezuma Creek in relationship to the lowest point in the Blanding Basin. The attribute displayed is elevation in metres. Surface topographic features are projected onto the basement grid.

scale and type of data, the method of interpretation, and the geological setting of the study area. Unfortunately, repeated misuse of these techniques has lead to the criticism of the whole of remote sensing as "geo-art" and has left many structural remote sensing researchers scrambling to justify their methods (Drury, 1987).

Figure 5 shows a 2D GIS overlay of the basement faults on the surface DEM data. This demonstrates various degrees of correlation of surface topographic features with interpreted basement faults. For example, it is evident that the Comb Ridge Monocline corresponds to the position of a major subsurface fault. In contrast, the San Juan River position, which has been interpreted as being fault controlled, can be seen to correspond to three different sub-surface fault segments, not just one. Note that Baars (1981) has suggested that the position of the San Juan River to the west of the study area is modified by Recent aeolian deposits. At the opposite extreme, although the major NE-SW-trending basement fault associated with the Coconino Lineament has a decided surface expression, the position of the sub-surface structure coincident with the Four Corners Lineament is less distinctive and would not be evident in a 2D image lineament interpretation alone.

Montezuma Creek is the second largest drainage in the study area and has a linear surface expression traditionally attributed to fault control. When comparing the position of Montezuma Creek to subsurface features, there is no associated sub-surface fault. However, comparing the surface DEM with the depth to the basement in a 3D display (Figure 6), it is evident that the position of Montezuma Creek corresponds to the topographically lowest point in the ancestral Blanding Basin, which suggests an alternative causal relationship. These relationships are easily verified through the incorporation of geophysical horizons between the surface and the basement.

The results of this study suggest that the relationship between surface topography and sub-surface structures is more complex than is generally assumed in traditional two-dimensional image lineament analysis. Three-dimensional display of DEM data with gravity and magnetic data yields a more complete interpretation for subsurface exploration.

Automatic Strike and Dip Determination

Automated determination of strike and dip measurements from remotely sensed imagery can greatly improve structural interpretation, and has been demonstrated in several areas. Morris (1991) successfully applied these techniques in the Snowdonia National Park, United Kingdom, with Airborne TM data at a 5-m resolution and DEM data derived from digitized contours scaled to 5 m. The computed strike and dip measurements are within 5° of field measurements (Morris, 1991). Researchers at Imagerie Stereo Appliquee au Relief (ISTAR, 1992) in France have demonstrated, using SPOT image data and image-derived DEM, that similar automated techniques can be applied successfully at a 20-metre resolution. Lang *et al.* (1987 and pers. comm.) have demonstrated the use of automatic strike and dip determination in combining Landsat TM data (30-m by 30-m resolution) and USGS 7.5-minute DEM (30-m by 30-m resolution) to map geologically in the Big Horn Basin, to a scale of 1:25,000. It is important to emphasis that in all three of these studies areas the surface geology is exposed on a relatively flat surface where variation in elevation is a direct reflection of the structural dip of the beds.

To test automatic strike and dip techniques on this study area, software developed at University College, University of London, by Kevin Morris was used. A trial was made with USGS 1° DEM which has a spatial resolution of 70 by 90 metres. The image data were from a decorrelated principal components image from Landsat TM bands 1,4,5, and 7, in which the first three PCs were displayed in RGB. The image and DEM data were rectified to the state-plane coordinate system and the image data were resampled to 70 m by 90 m to match the DEM resolution. Validation was with USGS map data and field survey of the study area.

Although there was an adequate match for the construction of an overlay of image and DEM for regional lithologic interpretation, there undoubtedly was registration error introduced due to the warping and rectification of the image data independently of the DEM. This, in combination with the poor vertical and horizontal accuracy of the 1° DEM data, led to failure of these methods to consistently estimate the true strike and dip of the units. There is a good surface exposure of lithologic boundaries; however, they are exposed on cliff faces rather than on a relatively flat surface. The fact that the lithologic contacts in the Utah study area are located on cliff faces that range between vertical to 40° complicates the application of automatic strike and dip calculation and will require a very accurate match between the image and the DEM data.

This study has proven that a data spatial resolution of 70 m by 90 m is not adequate for the use of automated strike and dip determination in an area that has this type of exposure. An evaluation of these methods using the full resolution TM data and USGS 7.5-minute DEM data is currently in progress.

Lithology Interpretation

The traditional method for rock type discrimination is described by Drury (1987). Information provided by the spectral characteristics of the terrain is important and is best portrayed in multispectral color composite images. For this study, a stretched false-color composite, using bands 1,4,5 in RGB, respectively, was found to be preferable to principle components methods.

In this study, the integration of co-registered image data and DEM data displayed in three dimensions was found to significantly increase the ease of interpretation of rock types. A portion of the surface lithology model is shown in Figure 7. The area is the southern part of Comb Ridge displayed with 30-metre pixel resolution (DEM 70- by 90-m data resampled to 30 m by 30 m). Due to the low sun angle at the time of imaging, much of the NW portion of Comb Ridge is in shadow. But the integration and 3D modeling can overcome this problem. Lithological contacts are associated with subtle slope breaks on the cliff faces. Thus, through interpretation on the southern faces of the cliffs of spectral variance in the image associated with lithology contacts, and identified with a slope break in the DEM data, the lithologic contacts can be extrapolated to the northwestern shadowed areas. The SGM software allows the interpreter to produce a variety of perspective views through interactive rotation of the model on screen. These factors greatly improve the interpretation of the surface geology.

Conclusions

The methods used in this study have demonstrated the usefulness of this approach as a petroleum exploration tool. The advantages are

- The combined modeling of basement structures and topographic features gives the structural interpreter a better understanding of the relationship between surface topography and sub-surface structure. The results of this study suggest that the traditional two-dimensional lineament analysis approach is over simplified. More studies, using the methodology described here on a variety of structural settings, are needed to fully understand how topographic expression relates to sub-surface structural geology. In the meantime, studies of satellite imagery should use a combination of the traditional 2D lineament analysis approach and the methods described here to interpret structural detail.
- The integration of co-registered DEM data and image data displayed in three dimensions is a more effective method for interpreting surface lithology than the traditional 2D image interpretation approach. The results of this study demonstrate that, through a 3D combination of the DEM and image data, the distribution of lithology is easily interpreted and better understood.
- The use of automatic strike and dip algorithms in study areas of this type is expected to be unsuccessful at the DEM resolution on the order of 70 by 90 metres, and higher resolution DEM data are recommended.

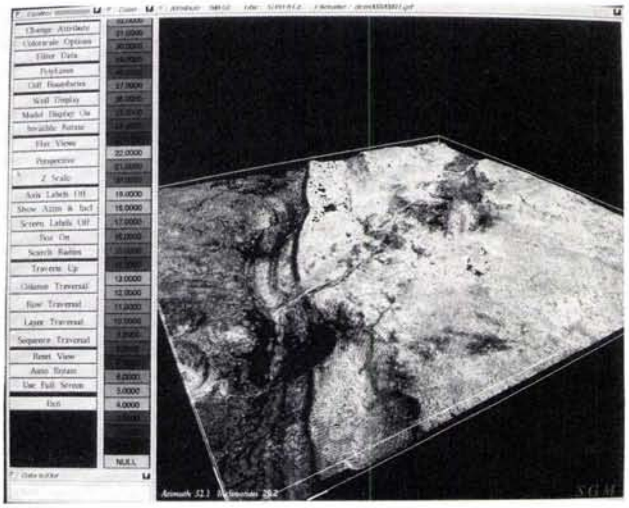


Figure 7. SGM digital terrain model of a portion of the Comb Ridge Monocline. Image data are a false-color composite of bands 1,4,5 in R,G,B, respectively. The 70- by 90-metre DEM data have been resampled to 30 by 30 metres to match the image resolution.

Although the full potential of this methodology has yet to be tested, it is envisioned that, using these methods, 3D models can be constructed from remotely sensed data sources, such as satellite imagery, and gravity and aeromagnetic surveys, to gain an understanding of regional geological relationships. This provides a low-cost method that could be utilized in the early stages of petroleum exploration. The initial model can be later expanded by including intermediate horizons constructed with either geophysical data or well-log data to unravel the full geologic history of a given sedimentary basin. Results can then be used in conjunction with established basin analysis techniques.

Acknowledgments

This work was supported by Texaco Inc., The Petroleum Science and Technology Institute (PSTI), and The AAPG Grant-in-Aid Program. Special thanks to Texaco and The Petroleum Science and Technology Institute for allowing for this work to be published. The paper published here is PSTI contribution No. 8.

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