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Report of the

Workshop on Geologic Applications of Remote Sensing to the Study of Sedimentary Basins

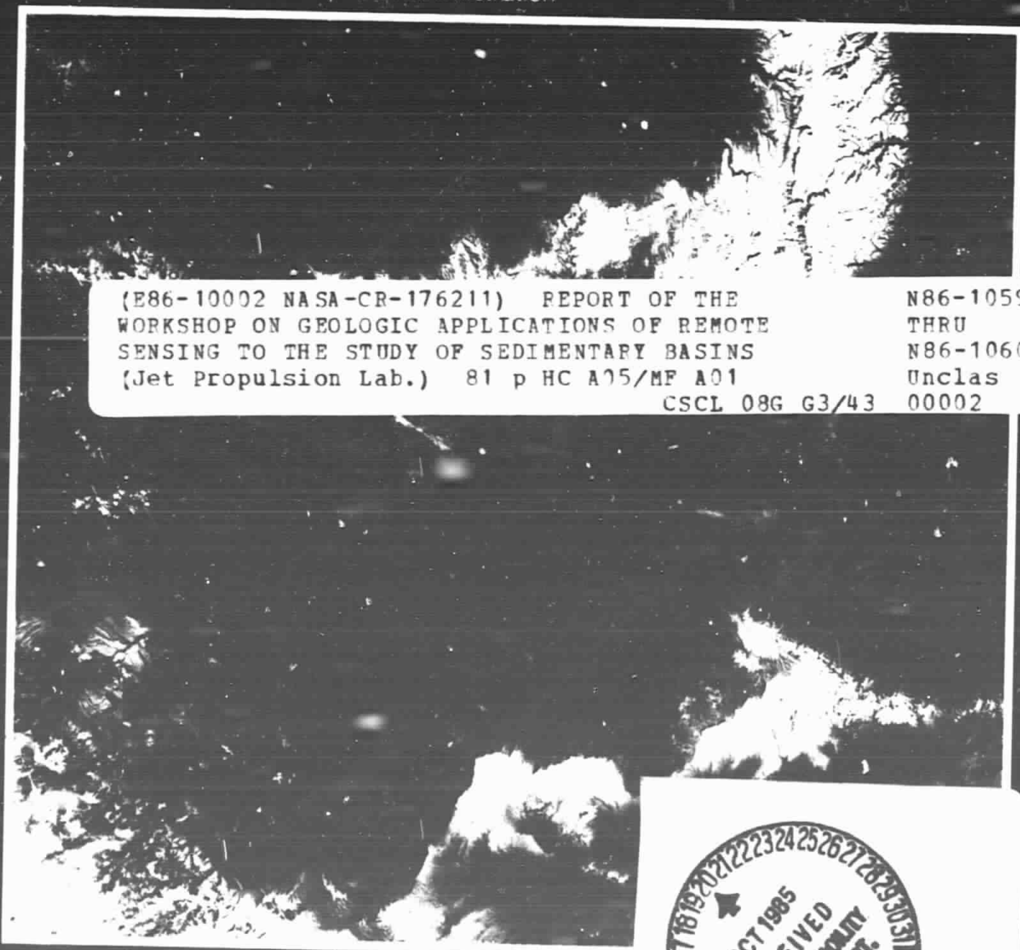
Lakewood, Colorado
January 10-11, 1985

Sponsored by the

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

under the auspices of the

Earth Science and Applications Division
National Aeronautics and Space Administration



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Edited by
Harold Lang

August 1, 1985

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ABSTRACT

The Workshop on Geologic Applications of Remote Sensing to the Study of Sedimentary Basins, held January 10-11, 1985 in Lakewood, Colorado, involved 43 geologists from industry, government, and academia. Disciplines represented ranged from vertebrate paleontology to geophysical modeling of continents.

Deliberations focused on geologic problems related to the formation, stratigraphy, structure, and evolution of foreland basins in general, and to the Wind River/Bighorn Basin area of Wyoming in particular. Geological problems in the Wind River/Bighorn Basin area that should be studied using state-of-the-art remote sensing methods were identified. These include (1) establishing the stratigraphic sequence and mapping, correlating, and analyzing lithofacies of basin-filling strata in order to refine the chronology of basin sedimentation, and (2) mapping volcanic units, fracture patterns in basement rocks, and Tertiary-Holocene landforms in searches for surface manifestations of concealed structures in order to refine models of basin tectonics. Conventional geologic, topographic, geophysical, and borehole data should be utilized in these studies. Remote sensing methods developed in the Wind River/Bighorn Basin area should be applied in other basins.

CONTENTS

ACKNOWLEDGMENT

Opinions, recommendations, and conclusions summarized in this document are those of workshop participants and do not necessarily represent the policy and program direction of NASA or JPL. The 43 attendees are thanked for their enthusiastic participation. Tom Fouch of the U.S. Geological Survey (USGS) kindly made arrangements for use of the Survey's Division of Continuing Education Facility, Denver Federal Center, as a meeting site. Helen Paley, JPL, and Charlene Barnhorst, USGS, provided logistic assistance for the meeting. Helen Paley also assisted in editing and coordinating the publication of this document. Jim Conel, Diane Evans, Tom Logan, J. D. Love, Ron Marrs, and Earnest Paylor provided useful suggestions for the workshop summary.

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SECTION I

SUMMARY

BY HAROLD LANG

A. BACKGROUND

The 1983 report of the Committee on Opportunities for Research in the Geological Sciences, National Research Council and National Science Foundation, stated that the next decade of geologic research should emphasize programs that increase our understanding of the structure, composition, and evolution of the continental lithosphere. Development of quantitative models of sedimentary basin evolution was selected as one of the eight most important research topics for advancing the science. Satellite remote sensing was specified as a tool that could contribute significantly to continental lithosphere research.

Remote sensing "refers to all of the arts and techniques of measurement and interpretation of phenomena from afar . . . specifically . . . the use of electromagnetic radiation to obtain data about the nature of the surface of the earth" (Goetz and Rowan, 1981, p. 781). Over 50 years of experience with aerial photography has established remote sensing as a geologic mapping tool. Aerial photographs are today a well accepted and routinely used source of geologic information.

For 13 years the Multispectral Scanners (MSS) on board Landsat satellites have imaged the Earth. Digital MSS data are objective, grid-sampled physical measurements. They provide unique synoptic observations of the Earth's surface and can be computer processed to enhance and display surface features of interest to geologists. Areas inaccessible because of political, economic, or logistic constraints are observed repeatedly by Landsat. MSS data are thus a versatile data source that could potentially be used in a broad range of studies of continental geology (Williams and Carter, 1976).

Although today most geologists are aware of the existence of MSS data, only a few remote sensing specialists actually use the data routinely. In part, this lack of use is the result of the coarse, 80-m spatial resolution of MSS data, useful mainly for reconnaissance mapping at scales of 1:100,000 or smaller. Additionally, continental geologists tend to be skeptical of "new" technology: they believe that there is a lack of convincing evidence that satellite data have been used to discover anything new that was of significance to their research. Such views are expressed in a recent basin analysis text:

> "One new mapping technique that has generated some interest recently is the use of satellite imagery to locate subtle structures in a search for giant oil and gas fields. So far the technique has only been used retrospectively. . . . The results are singularly unconvincing. Vague tonal changes or disconnected lineaments are apparent, but in most cases bear little or no relationship to the fields. It seems unlikely that such

images will ever be of more than passing interest for basin mapping purposes, even for the remotest frontier regions, where the real reconnaissance work is based on conventional air photography and aerial geophysics" (Miall, 1984, p. 213-214).

The validity of these opinions may be debated, reflecting as they do an examination of one MSS study, but they may represent the views of many continental geologists. Basin analysis aided by satellite remote sensing may have been identified by a committee as an important geologic research topic of the 1980s, but aerial photography is the only remote sensing tool routinely being used for geologic mapping. Most geologists know that Landsat MSS digital remote sensing data exist, but do not use such data and are skeptical of their value. Experimental remote sensing data, available since 1982 (Table 1), are unknown to most geologists, and are used by a relatively small cadre of remote sensing specialists primarily interested in systems engineering, sensor development, and computer processing.

In 1984, geologists from the Geology and the Radar Remote Sensing Groups at JPL and the University of Hawaii studied the Wind River/Bighorn Basin area, Wyoming (Figure 1). The purpose of the investigation was to evaluate the feasibility of using state-of-the-art satellite and aircraft remote sensing surveys (Table 1) for stratigraphic and structural analysis in a North American, western interior, sedimentary basin. Initial results, reported by Evans and Schenck (1984), Lang et al. (1984), Paylor et al. (1984), and Conel et al. (1985), demonstrate that new information obtained from multisensor, multispectral remote sensing surveys can contribute significantly to regional (1:250,000) and detailed (1:24,000) stratigraphic and structural analyses. Remotely sensed data and observations from surface, borehole, and geophysical surveys potentially can be combined to better constrain models of the three-dimensional geometry, and stratigraphic and structural history of the Wind River/Bighorn Basin area. Based on these results, a 3-year basin analysis research program was proposed and accepted by NASA for funding. The formation and evolution of the Wind River/Bighorn Basin will be studied with remote sensing surveys supported by field, laboratory, topographic, geologic, borehole, and geophysical data. Strategies of data acquisition and methods of geologic analysis developed in the Wind River/Bighorn Basin area could be used to study similar continental basins elsewhere.

B. PURPOSE OF THE WORKSHOP

All too often geologists in specific disciplines fail to utilize information and ideas developed in other disciplines. This is especially true of geologists involved in remote sensing research, a discipline commonly isolated from the mainstream of continental geology research and often considered a black box science by much of the geological community. It was therefore considered imperative at the outset of the Wind River/Bighorn Basin study to establish a dialogue with Earth scientists possessing expertise in basin analysis and modeling, and in-depth geological knowledge of the study area. Hence, a Workshop on Geologic Applications of Remote Sensing to the Study of Sedimentary Basins was convened by JPL under the auspices of NASA's Earth Science and Applications Division.

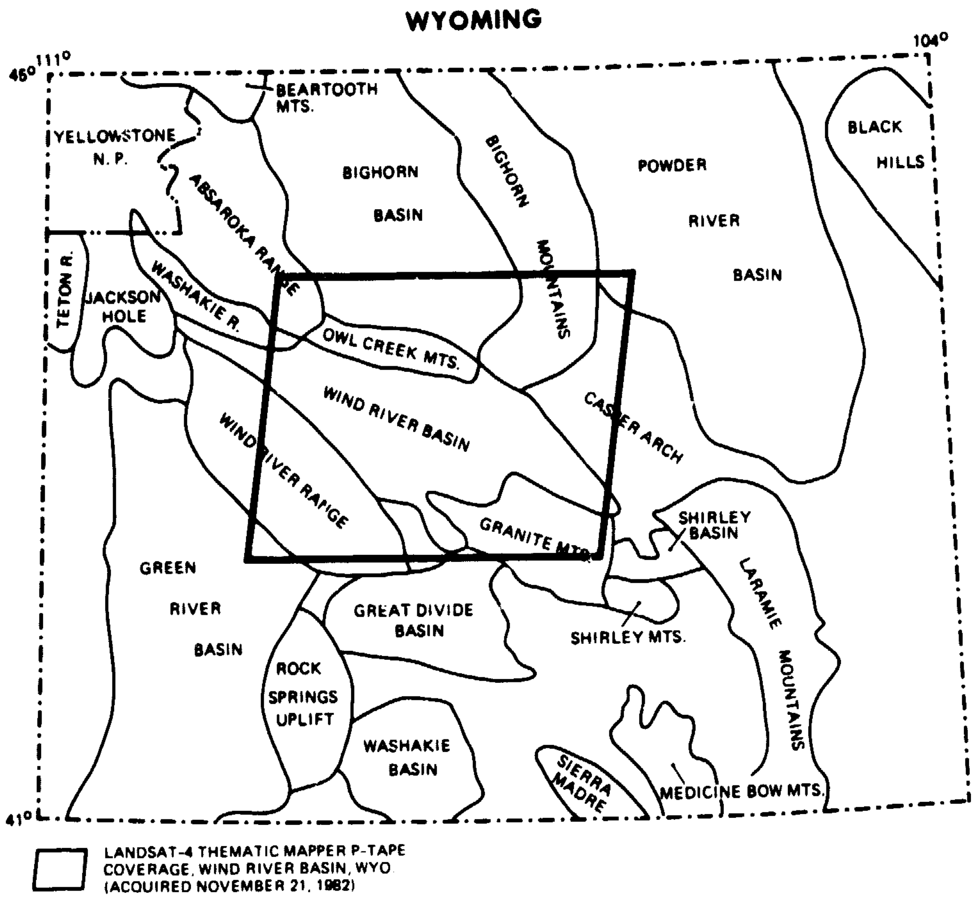

Figure 1. Physiographic map of Wyoming showing the location of the Wind River/Bighorn Basin study area depicted on the cover picture. Major features are after Love (1970).

Table 1. Remote Sensing Systems Available for Basin Studies

Sensor (Date Available)	MSS[a] (1972)	TM[b] (1982)	AIS[c] (1982)	TIMS[d] (1982)	L-Band SAR[e] (1978)	Quad-Pol. SAR[e] (1983)
Platform	Landsat 1-5	Landsat 4-5	Aircraft	Aircraft	Seasat	Aircraft
Altitude	900 km*/700 km**	700 km	5 km***	10 km***	800 km	10 km***
Swath Width	185 km	185 km	290 m***	4 km***	100 km	6 km***
Wavelength	0.50–0.60 μm	0.45–0.52 μm	1.2–2.4 μm (128 bands)	8.1–8.5 μm	23.5 cm	23.5 cm
		0.52–0.60 μm		8.5–8.9 μm		
	0.60–0.71	0.63–0.69 μm		8.9–9.3 μm		
	0.69–0.80	0.76–0.90 μm		9.5–10.1 μm		
	0.80–1.1	1.55–1.75 μm		10.2–10.9 μm		
		2.0–2.36 μm		11.2–11.7 μm		
		10.4–12.5 μm				
Pixel Size	80 m	30 m (0.45–2.36 μm) 120 m (10.4–12.5 μm)	9 m***	25 m***	25 m***	10 m***

*Landsat 1, 2 and 3
**Landsat 4 and 5
***Typical

[a]Multispectral Scanner
[b]Thematic Mapper
[c]Airborne Imaging Spectrometer
[d]Thermal Infrared Multispectral Scanner
[e]Synthetic Aperture Radar

C. PARTICIPANTS AND OBJECTIVES

The workshop, held January 10 and 11, 1985, at the U.S. Geological Survey's Division of Continuing Education in Lakewood, Colorado, included 43 invited participants (Appendix A) from industry, government, and academia. Deliberations focused on geological problems encountered in the study of continental sedimentary basins (Figure 2). The goal was to promote direct multidisciplinary interchange among Earth scientists that could potentially lead to cooperative research. Geological disciplines represented at the workshop ranged from vertebrate paleontology to geophysical modeling of the continents. Most participants were Earth scientists and not remote sensing specialists.

Workshop objectives were (1) to identify significant, unresolved, scientific questions related to the formation, stratigraphy, structure, and paleogeographic and tectonic evolution of foreland basins in general, and the Wind River/Bighorn Basin area of Wyoming in particular; (2) to examine the state of the art of geologic remote sensing methods; (3) to evaluate the potential combined utility of surface and subsurface geological, geophysical, and remote sensing methods for addressing basin research problems; and (4) to recommend specific remote sensing experiments for the Wind River/Bighorn Basin project that address questions identified in item (1).

Participants were encouraged to be as technically provocative as possible. Speculation about untested hypotheses or implications of earlier research related to the formation and evolution of sedimentary basins was welcomed.

To facilitate discussions, participants were invited to arrive at the meeting with concise position papers and illustrative materials summarizing their views (Appendix B). Additionally, participants were asked to complete a questionnaire designed to identify basin research problems that are amenable to study with remote sensing methods (Appendix C). The questionnaire also served as an agenda for topical discussion group deliberations (Appendix D).

The meeting agenda (Appendix E) provided for

(1) Invited background presentations before all participants.

(2) Breaking into small topical discussion groups to identify salient research problems and to suggest possible aspects of basin research that might be aided by remote sensing observations.

(3) Summary and discussion of results from items (1) and (2).

D. BACKGROUND PRESENTATIONS

1. NASA-Sponsored Geologic Research

The workshop opened with a presentation by Catherine Kitcho of NASA Headquarters outlining NASA's Geology Program. Kitcho noted that the goal of NASA's Land Processes - Geology Program is to develop improved understanding of the composition, structure, and evolution of the Earth's crust through the

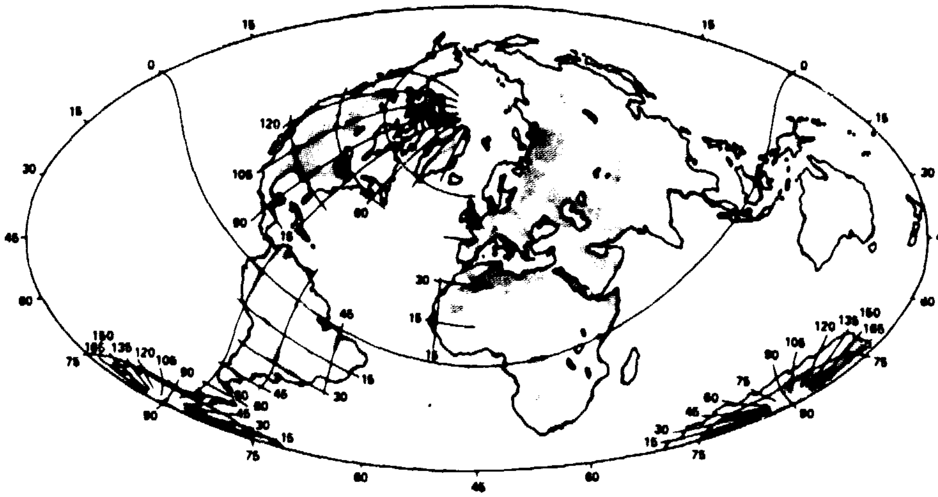

Figure 2. Major continental sedimentary basins of the world. Sedimentary basins are major crustal depressions that are (1) the repositories of sedimentary rocks recording the depositional and tectonic history of continental crust during the Phanerozoic, (2) the sources of renewable and nonrenewable resources, and (3) the sites of major population centers. Our understanding of the Earth's history, utilization of resources, and mitigation of geologic hazards depends upon a knowledge of the sedimentary and structural history of these basins. (Basin data after St. John, 1980; Nordic Projection after The Times, 1980).

use of space technology. Objectives are (1) to conduct basic geological research in order to define the composition, structure, and distribution of rocks on a global basis; (2) to utilize orbital remote sensing technology for first-order Earth exploration; and (3) to derive multidisciplinary/ multispectral methodologies for maximizing the geological data yield from remote sensing technology. To accomplish these goals and objectives, NASA sponsors research in Earth science, sensor development, and data processing. Table 2 outlines some elements of this research program as proposed in 1985. Kitcho stated that the present workshop was sponsored by NASA to obtain recommendations from geologists regarding the sedimentary basin research element.

Tom Fouch, Coordinator of the U.S. Geological Survey's Evolution of Sedimentary Basins Program, commented that the Survey was in the process of planning comprehensive studies of six North American sedimentary basins. He noted that the workshop deliberations could contribute to the Survey's formulation of a research plan for this new program.

2. Geologic Setting of Wind River/Bighorn Basin Area

Four invited presentations provided background geologic information concerning Wyoming basins, with particular reference to the Wind River/Bighorn Basin area:

(1) The geologic setting of Wyoming foreland basins (Dr. J. D. Love, USGS).

(2) The structure and tectonics of the Wind River/Bighorn Basin area (Dr. D. Blackstone, University of Wyoming).

(3) The stratigraphic evolution of the Wind River/Bighorn Basin area (Dr. D. Keefer, Mitchell Energy, Inc.).

(4) Stratigraphic evidence for Pre-Laramide structural control on Wyoming foreland evolution (Dr. J. Peterson, USGS).

The four scientists making these presentations brought a combined total of nearly two centuries of basin research experience to the workshop. They pointed out that Wyoming basins are stratigraphically and structurally part of a system of foreland basins occurring over the entire length of the Cordilleran Orogen from Alaska to South America.

Intermountain basins cover nearly one-half the area of Wyoming (Figure 1). Blackstone observed that Wyoming basins are major deflections of the continental lithosphere exhibiting up to 15 km (48,000 ft) of relief. Love reported that the Wind River and Bighorn Basins exhibit 10 km (33,000 ft) of relief. These basins have similar structural and sedimentalogical histories.

Before Cretaceous time, Wyoming was part of a vast foreland lying along the east side of the Cordilleran geosyncline, where the thickest accumulation of marine Paleozoic sediments occurred. Keefer reported that rocks representing all systems except the Silurian are present in the Wind River/Bighorn Basin area.

Table 2. Outline of NASA's Land Processes - Geology Program, Proposed FY 1985 Program Elements

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Basic Geological Research
- Plate Tectonics/Continental Rifts/Volcanism
- Evolution and Composition of Sedimentary Basins
- Studies of Oceanic Crust/Ophiolites
- Rock Weathering and Erosional Processes

Earth Exploration
- Arid Regions
- Tropical Regions
- Polar Regions

Multidisciplinary Research
- Geobotany
- Arid Lands Ecology
- Multispectral Analysis

Sensor Development and Data Processing

During early Cretaceous time, the locus of maximum sediment accumulation moved eastward with orogenic uplift of the Cordillera. Marine waters withdrew to the east, but episodic readvances of the seas westward resulted in complex marine and nonmarine sedimentation ending with the close of the Cretaceous Period. Nonmarine sediments were deposited in swamps, lagoons, and deltas. The principal sediment source was a belt of rising Cordilleran highlands to the west.

Major deformation of the Laramide Orogeny began in Late Cretaceous time and continued into the Eocene. Sediments were deposited in elongate subsiding troughs from surrounding uplifts. At times, an interconnected system of such troughs extended from the present Arctic Ocean to the Gulf of Mexico. Commensurate with Paleocene time, uplifts separated these troughs into individual basins. Maximum Laramide deformation occurred during Early Eocene time when mountain upwarps moved basinward along thrust or reverse faults overriding margins of individual basins.

According to Blackstone, Laramide foreland deformation involved Precambrian "basement." The deformation typically resulted in asymmetric folding, structural deepening, and thickest sediment accumulation along basin margins nearest thrusting. Peterson reported that major facies changes within Permian stratigraphic units record Pre-Laramide control on some major Laramide structures. He noted that these Pre-Laramide trends are expressed by fracture patterns in Precambrian basement rocks and both Pre- and Post-Laramide strata, an observation confirmed by Keefer.

Recent seismic, gravity, and borehole data have revealed the deep structure of the Wind River Range, Casper Arch, and Bighorn Mountains as shallow dipping thrust faults associated with major décollements. Thrusts extend to depths of at least 24 km and possibly to the Moho. These thrusts imply that Laramide deformation is the result of extensive NE-SW horizontal compression (locally over 21 km) and minimum vertical displacement of over 13 km. According to Blackstone, this information provides significant new evidence for resolving the ongoing debate about the relative importance of vertical vs. horizontal tectonics in Laramide foreland deformation in Wyoming; horizontal tectonics is favored.

Commencing in the Eocene and continuing through most of the Tertiary, eruptions emanating from the Absaroka Volcanoes produced flows that covered much of the southwest margin of the Bighorn Basin. Oligocene, Miocene, and Pliocene rocks in the Wind River/Bighorn Basin area are predominantly tuffaceous volcaniclastics, according to Keefer. By late Tertiary time the entire study area was largely covered with tuffaceous volcaniclastics, and only the highest peaks were still exposed. Blackstone reported that this volcanic cover today masks much of the Pre-Tertiary structure and stratigraphy of the western Bighorn Basin.

According to Blackstone and Keefer, regional uplift of the area commenced in Late Miocene time. By Middle or Late Pliocene time, mountains and basins were uplifted 1000 m (3000-4000 ft) and re-excavation of the Wind River and Bighorn Basins initiated. Love pointed out that this excavation, at a rate of 1 ft/1600 years (0.2 m/1000 years) over the last 3 million years, records locally a major isostatic readjustment of much of the western margin of the North American continent.

These Late Tertiary readjustments resulted in normal faulting and collapse of major Laramide uplifts near the toes of former thrust or reverse fault zones. Uplifts of basin margins continued into the Pleistocene and Holocene. Keefer reported that this complex history of Laramide and Post-Laramide sedimentation and deformation is today expressed in the Wind River Basin by over 6 km (20,000 ft) of relief measured on the top of the Permian.

Drainage of the Wind River/Bighorn Basin area in the present epoch is to the north. Today the area is semiarid and relatively sparsely vegetated, and offers excellent exposures of Precambrian through Holocene units on basin margins and Cretaceous through Holocene strata in the basin interior. Although much is known about this nearly complete Phanerozoic record of the evolution of the western North American Continent, Keefer pointed out that major stratigraphic problems are still unresolved, especially in Cambrian, Ordovician, Permian, Triassic, and latest Cretaceous strata. A new 1:500,000 geologic map of Wyoming (Love and Christiansen, 1985), shown in color for the first time at the meeting by Love, represents the most complete published compilation of surficial geologic information available for the Wind River/Bighorn Basin area.

3. Remote Sensing in Sedimentary Basin Study

Two presentations provided examples of the application of remote sensing data to the study of sedimentary basins:

(1) The use of Landsat images and seismic reflection data for identifying subtle foreland structures (Dr. Z. Berger, EXXON Production Research).

(2) Initial results of an evaluation of new remote sensing surveys for stratigraphic and structural analysis of the Wind River/Bighorn Basins (Dr. H. Lang, JPL).

Berger described the utility of photogeology in searches for zones of structural weakness that are repeatedly reactivated during basin formation and evolution. These zones are expressed by subtle linear alignments of topographic, drainage, vegetation, or lithologic discontinuities (lineaments) that are transverse to regional structural grain. Photogeologic interpretation of MSS, TM, radar images, and aerial photographs has been successfully used to locate such discontinuities. These zones of structural weakness are commonly expressed in the subsurface as subtle structural and stratigraphic disruptions that are frequently missed in initial interpretations of seismic reflection data. Once located using photogeology, however, such disruptions are commonly confirmed in reinterpretation of seismic and subsurface data. Berger emphasized the value of geophysical data, specifically seismic reflection data, in conjunction with photogeologic interpretation of image data for structural analysis of sedimentary basins.

Lang described the sedimentary basin study that is being conducted by geologists from JPL and the University of Hawaii (see position papers by Blake et al., Conel, Evans et al., Lang et al., and Paylor, Appendix B). He noted that prior to 1982, inadequate spatial resolution and spectral coverage limited the utility of remote sensing data for geologic study of sedimentary basins. TM, AIS, TIMS, and SAR data (Table 1) now provide improved spatial and spectral resolution, cartographic fidelity and spectral coverage. The geologic utility of these new remote sensing data was evaluated in the Wind River/Bighorn Basin area of central Wyoming (cover picture and Figure 1).

Combined photogeologic, image processing, and spectral analysis methods were used to (1) map strata on the margins and interior of both the Wind River and Bighorn Basins at scales of 1:250,000 and 1:24,000; (2) measure the dip and strike of bedding planes and faults; (3) construct "spectral stratigraphic" columns incorporating thickness, resistance, and mineralogic information derived from remote sensing data alone; (4) correlate a Permian-Upper Cretaceous spectral stratigraphic column constructed in the Wind River Basin with (a) a conventional column measured in the field, (b) a spectral stratigraphic column constructed in the Bighorn Basin, and (c) geophysical well logs; and (5) construct structural cross sections based on image interpretations and constrained by borehole data and a concentric fold model. Topographic data were essential for this work. Significant geologic results of these exercises include recognition of previously unreported thrust faults in the southern Bighorn Basin, identification of an increase in thickness of the Muddy Sandstone Formation on the western flank of the Casper Arch, and determination of the stratigraphic distribution of dolostone, limestone, gypsum, bentonite, and redbeds in Permian-Upper Cretaceous strata exposed in the northern Casper Arch-southern Bighorn Mountains area of the eastern Wind River Basin.

Comments following this presentation indicated that some of the geologic results described are confirmed by unpublished and proprietary geological mapping and geophysical data. Lang concluded by stating that these results demonstrate the utility of new remote sensing data for structural and stratigraphic studies in sedimentary basins and the complementary nature of remote sensing and conventional methods for studying the formation and evolution of sedimentary basins.

E. TOPICAL DISCUSSION RESULTS

Group discussions focused on basin research topics, specifically Pre-Laramide Stratigraphy, Post-Laramide Stratigraphy, Structure/Tectonics, and Data Integration (Appendix D).

It was generally agreed that basic scientific and practical reasons justify study of the formation and evolution of sedimentary basins. Most groups decided that the term "basin analysis" is somewhat ambiguous; its meaning is dependent on the interests, backgrounds, and goals of individual researchers. The Post-Laramide Stratigraphy Group defined basin analysis as "the study of the stratigraphic (depositional and erosional events), structural/tectonic, and biological history of a sedimentary basin." This definition reflects the concensus view that basin analysis is an interdisciplinary endeavor that utilizes all tools that contribute to understanding sedimentary basins in time and space. New remote sensing methods may be one such tool.

There was considerable debate as to whether the Wind River/Bighorn Basin area, because of its stratigraphic/structural complexity and long history of geologic investigation, was an ideal location to test this tool. But it was agreed that the area represented a challenging location to develop new remote sensing methods to be tested in other less-studied continental basins.

The Pre-Laramide Stratigraphy Group did not recommend specific research problems in the Wind River/Bighorn area, but rather outlined general elements of stratigraphic research that would benefit most from the basin-wide perspective provided by remote sensing. These include facies identification and correlation, relationship between structural patterns and sedimentation, geochronology, and evaluation of basin models. Biostratigraphic, paleomagnetic, radiometric dating, and conventional sedimentologic data were identified for use in conjunction with remote sensing data.

The Post-Laramide Stratigraphy Group reiterated the general research elements identified by the Pre-Laramide Group. They also identified 12 specific research problems in the Wind River/Bighorn Basin area. These included detailed mapping, correlation, and facies analysis of the relatively poorly mapped Tertiary-Holocene basin fill. Aerial photographs, topographic data, and conventional field observations were identified as important sources of information to be used in conjunction with remote sensing methods.

The Structure/Tectonics Group recognized the importance of the stratigraphic research elements identified by the two stratigraphy discussion groups. They identified seven specific research problems in the Wind River/Bighorn Basin area. These included mapping the Absaroka Volcanics, mapping fracture patterns in basement rocks exposed on basin margins, and mapping Tertiary-Holocene basin fill--all in searches for subtle surface manifestations of "hidden" structures, particularly buried or concealed faults. The group emphasized the value of seismic data for use in conjunction with remote sensing methods.

The Data Integration Group recognized that recent advances in the acquisition and integration of digital geological/geophysical data have probably outstripped understanding of their geological meaning. The group emphasized that computer data integration for basin studies must be based upon sound geologic models; disparate data sets should not be "merged" only because they exist.

F. CONCLUSION

Basic scientific and practical reasons justify study of the formation and evolution of sedimentary basins. This relatively short, two-day meeting promoted stimulating interdisciplinary discussions among 43 participants who shared interest in understanding these important features of the Earth's crust. Significant scientific problems relating to basin analysis were examined. The focus was geology, and researchers from disciplines ranging from geophysical modeling of the continents to vertebrate paleontology gained insight into the limitations and potential of new remote sensing tools for investigating continental sedimentary basins. Specific research problems in the Wind River/Bighorn Basin area that are potentially amenable to remote sensing methods were identified. The meeting thus accomplished all of its goals and objectives.

Many participants suggested that similar meetings involving remote sensing specialists and geologic researchers from other disciplines be held in the future in order to maintain and expand interdisciplinary contacts established at this meeting. Perhaps the best demonstration of the workshop's success is that deliberations resulted directly in the formulation of several interdisciplinary research proposals that will incorporate new remote sensing data and address specific geologic problems related to the formation and evolution of sedimentary basins.

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SECTION II

APPENDIXES

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APPENDIX A

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(INTERESTS - EXPERTISE)

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APPENDIX B

POSITION PAPERS

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Remote Sensing - Basin Analysis Workshop

Possible points of discussion

Anonymous

Geological

Information pertaining to the subsurface is of great interest to hydrocarbon exploration in basins such as that in western Canada. Remote sensing would be of most use to such exploration where the surface manifestations detected can be related to conditions in the subsurface.

Listed below are some subsurface conditions and their surface manifestations that might be discussed at this workshop with respect to their detectability through remote sensing.

1) geologic structure and its expression at the surface as lineaments associated with faults and/or joints.

2) geologic structure such as faults and/or joints and their detection through gas leakage.

3) hydrocarbon accumulations and their detection through gas leakage (e.g. direct detection of gas or through geobotanical analysis).

4) hydrodynamics of a basin through identification of recharge and discharge areas as expressed by differences in vegetation, distribution and intensity of springs, seeps, soil, thermal anomalies, erosion and salinization.

Point 4 could be relevant to hydrocarbon exploration in light of hydrological investigations in the last decade which have shown a relationship between groundwater migration paths and petroleum occurrences (e.g. Toth, 1980; Hitchon, 1984). These studies have led to a hydraulic theory of petroleum migration which states that topography induces cross-formational groundwater flow which has a genetic effect on hydrocarbon accumulation. Specifically, it has been demonstrated that groundwater flow in a basin is distributed in systems on local, intermediate and regional scales. Where systems meet, part, or change direction, zones of slow water movement or stagnancy develop. Hydrocarbon accumulations have been found to be preferentially associated with ascending limbs and stagnant zones of groundwater flow fields. In conjunction with any hydraulic studies conducted in a basin, remote sensing may aid hydrodynamic modeling by identifying discharge (i.e. ascending limbs) areas from surface manifestation. Some of these surface features include:

1) high salinities in stagnant zones and discharge areas (ultimate expression = salt accumulations but more subtly may show up as a geobotanical stress).

2) moisture availability; high in discharge area, low in recharge and effect on vegetation.

3) discharge areas show a concentration of springs and characteristic soil erosion (e.g. frost blisters).

4) temperature anomalies; positive = discharge
negative = recharge

Remote Sensing in General

1) Any new advances on the horizon? e.g., other Landsats planned with broader spectral coverage.

2) Will remote sensing coverage ultimately be the domain of the private sector?

3) Any advances in analysis of highly vegetated areas?

References

Toth, J. 1980. Cross-formational gravity-flow of groundwater: a mechanism of the transport and accumulation of petroleum (the generalized hydraulic theory of petroleum migration). AAPG Studies in Geology no. 10, Problems in Petroleum Migration, pp. 121-167.

Hitchon, B. 1984. Geothermal gradients, hydrodynamics, and hydrocarbon occurrences, Alberta, Canada. AAPG Bulletin, 68, pp. 713-743.

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N86-10600

SOME OPINIONS ON REMOTE SENSING AND GEOLOGIC STUDIES

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The principal role of remote sensing data in geologic studies is as a source of geologic information from which meaningful geologic interpretations can be made. Remote sensing cannot be portrayed as being the answer to all problems, but neither should it be viewed with unwarranted skepticism for lack of familiarity or experience on the part of geologists. Rather, it is simply one of many tools that must be applied, separately and in combination with other tools, in the solution of geologic problems to enable the investigator to derive the maximum amount of information relevant to the objective of his study.

Basic geologic information, both lithologic and structural, is important in the study of sedimentary basins. Landsat and other satellite data have been and will continue to be important sources of such information in addressing both regional and more local problems of sedimentary basin analysis. Systematic and comprehensive analysis and interpretation of Landsat multispectral scanner (MSS) data, with its four spectral bands and 80 m spatial resolution, have resulted in accurate regional geologic interpretations that have contributed measurably to a better understanding of important structural and stratigraphic relationships of major petroleum producing basins as well as to new insights about the tectonic evolution of such basins. Landsat MSS data comprise the only set of earth resource satellite image data available with worldwide coverage, and their value to hydrocarbon exploration and resource evaluation must not be overlooked. However, Landsat thematic mapper (TM) data and data from other new and future satellite and airborne systems provide significantly more spectral information and greater spatial detail than Landsat MSS data. Such data permit more detailed investigation of structural and stratigraphic characteristics and relationships, and they provide the opportunity to begin to realistically address and characterize such phenomena as hydrocarbon induced vegetation anomalies and surface alteration effects of hydrocarbon leakage.

Remote sensing data are important in sedimentary basin analysis and other geologic studies as independent and sometimes unique sources of important lithologic and structural information; however, their greatest benefit to exploration-oriented investigations may come when these data are used with other relevant data in a digital database approach to exploration. Modern computer technology facilitates the rapid integration and synthesis of satellite, topographic, gravity, aeromagnetic, geochemical, and other data collected from a given region. Once such data are geometrically registered, they can be digitally processed, within the constraints of defined geologic models, to rapidly identify, and focus further exploration efforts on, target areas that have the greatest potential for success.

In the 12 years since the launch of the first Landsat satellite, remote sensing for geologic applications has evolved from a little known and often unaccepted technique to an increasingly more respected and accepted part of geologic and exploration science. Great strides have been made in the technological and scientific advancement of remote sensing through research and development, yet the potential benefits to geologic studies from the application of remote sensing data are far from being fully realized. As greater volumes of increasingly improved airborne and satellite remote sensing data become available during the next several years, expanded systems develop programs and increased theoretical and applications research activities will be required to further advance the wider acceptance and effective utilization of remote sensing data and to more fully realize the significant potential benefits remote sensing offers to a great many earth science endeavors.

N86-10601

POSITION PAPER: WORKSHOP ON GEOLOGIC APPLICATIONS OF REMOTE SENSING TO THE STUDY OF SEDIMENTARY BASINS

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An important application of geological remote sensing data is to areas which have been incompletely explored and mapped. Under these circumstances the surface geology is either unknown or poorly known; consequently, regional relationships amongst exposed units have not been defined.

The utility of Landsat Multispectral Scanner and Thematic Mapper data for providing regional coverage has been demonstrated. Information derived from Landsat spectral data is varied, but has primarily been used for distinguishing materials in a scene. Because of the limited number and width of the MSS and TM bands, Landsat data has only limited utility for actual *identification* of materials.

The new advanced sensors (currently airborne, but eventually shuttle-based) have more limited areal extent than Landsat, but greater spatial and spectral resolution. The Airborne Imaging Spectrometer (AIS) has spectral resolution of about .01μm and, typically, has 10m/pixel spatial resolution. This improved spectral resolution means that diagnostic spectral features may now be identified, which in turn means that actual identification of mineral phases present can be addressed (of either monomineralic or composite materials). Another new sensor, the Thermal Infrared Multispectral Scanner (TIMS), obtains data in the 8-12μm range. While TIMS is still a broadband instrument, it differs from Landsat in that the 6 TIMS bands have been chosen to correspond to spectral features of known geologic interest.

The information from the various sensors (e.g. Landsat, AIS, and TIMS) is complementary, covering different wavelength regions and consequently sensitive to different materials or physical properties of materials. In addition, the new sensors also produce a higher volume of data, which must be cleverly and efficiently handled. Conventional analysis procedures, including visual examination of all the data as well as some statistical techniques, such as Principal Components, are less viable for these high volume data sets. Techniques are required which both take advantage of the variety of information available, while selectively reducing (through information extraction) the volume of data being handled: both integrating and information-based sorting processes must be developed.

Our work here is focussed on the problems of extracting geologic information from these large multidimensional, multisensor data sets. As part of the Wind River project we are investigating computer-based techniques for recognizing and mapping specific, geologically interesting spectral characteristics of lithologic units. A major objective of our research is explaining the physical processes responsible for observed spectral characteristics, thus although the techniques developed will be applied specifically to analysis of the sedimentary units in the Wind River area, they will be extendable to other areas and other geological characteristics.

N86-10602 D3

Chronologic Analysis of Terrestrial Sediments and Basin Evolution

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The initial phases of basin analysis typically consist of determination of the stratigraphic sequence within a basin and subsequent mapping of the geology in the study area. During the process of mapping, tectonic structures and discontinuities, as well as facies relationships, are examined. At this point, the basic elements are in hand for analyzing the basin development: the relative sequence of basin filling events, facies relationships and their distribution with respect to the paleogeography of the basin, and the syn- and post-depositional tectonic disturbance of the basin fill. These elements can be integrated into a detailed picture of basin evolution. The temporal control for such a synthesis would be provided by the relative sequence of events and any paleontological data. Correlations between widely separated areas would be based on lithostratigraphic and biostratigraphic data. Because of the time-transgressive nature of depositional events and the frequent paucity of paleontological data with precise chronologic control, such analyses would only be loosely constrained in a temporal framework. In areas where there is no direct physical connection, it would be difficult to examine the detailed relationships between tectonic events, facies changes, and depositional histories. The precise timing of these phenomena, as well as rates and changes in rates of processes within the basin (sediment accumulation, fault migration, uplift, facies migration, etc.), would be unresolvable.

In order to address these additional aspects of basin development, it is necessary to have detailed absolute chronologies in numerous areas within a basin. For the latest Cretaceous and all of the Cenozoic, magnetic-polarity stratigraphy can provide this sort of chronology. The global magnetic-polarity time scale is quite well known. Although the absolute ages of reversal boundaries will undoubtably be shifted somewhat in the future, the overall pattern of reversals and the relative duration of magnetozones are likely to be modified very little. Consequently, magnetostratigraphy provides a tool that can be used to erect detailed chronological frameworks for terrestrial sediments.

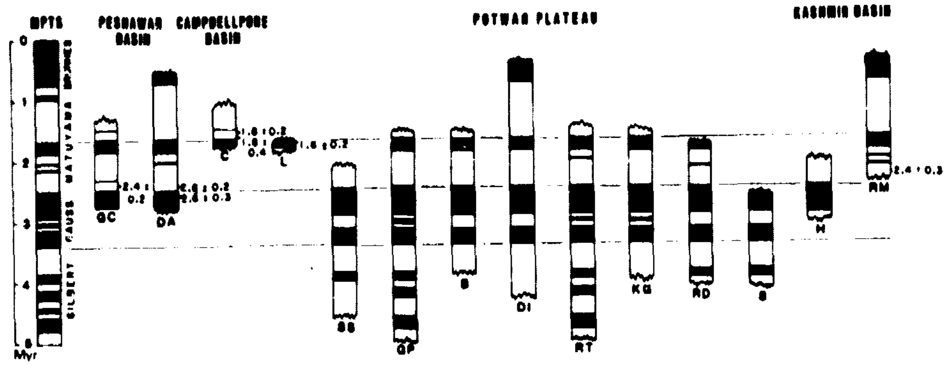
What sediments are suitable for magnetostratigraphic studies? Clays, muds, and silts are best for such studies, and fine grained sandstones (particularly with a lot of matrix) are also potentially useful. Freshwater limestones and even volcanic ashes can be good recorders of the magnetic field. Unoxidized sediments are best for magnetic studies, but red beds consisting of detrital hematite will work, too. However, many red beds contain authigenic hematite of post-depositional origin that obscures the original remanence.

What types of questions can be answered with magnetostratigraphic studies? First and foremost, correlation of the locally derived pattern of magnetic reversals with the global reversal time scale provides a chronologic framework with numerous well dated reversal horizons. In short duration sequences, the reversal pattern often may not be uniquely diagnostic. In these cases, either a radiometric date, such as on a volcanic ash, or some paleontological data with strong temporal significance can be used to "tie down" the local reversal sequence.

Once this chronologic framework is established in a number of localities, it becomes possible to begin a new phase of basin analysis. One can ask, "What was happening in different portions of the basin at a particular time?" The following sets of figures are intended to illustrate some of the applications of magnetic-polarity stratigraphies to various aspects of basin analysis. Most of the examples are drawn from the Himalayan molasse (Indo-Gangetic foredeep) in northern Pakistan and northwestern India.

Correlations between sections:

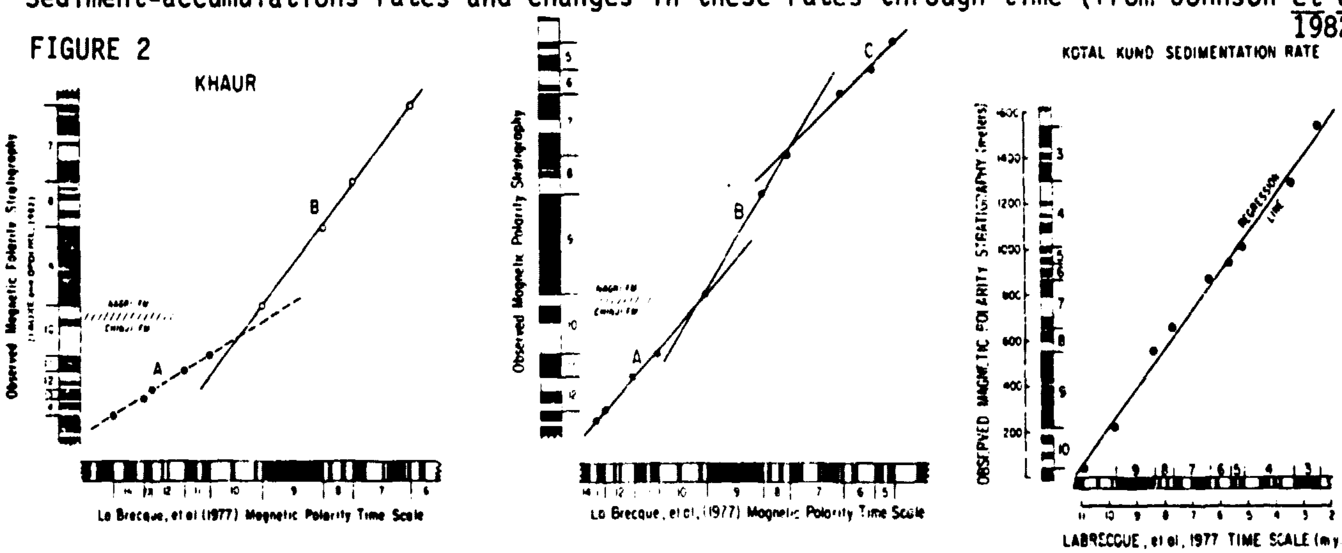
FIGURE 1



Comparisons of locally determined magnetic-polarity stratigraphies (MPSs) with the magnetic-polarity time scale[41,42]. Fission-track dates on volcanic ashes are shown with 2σ errors at their appropriate stratigraphical positions. The magnetostratigraphical correlations are based on recognition of identifiable chrons or subchrons and are aided by both fossil occurrences and the frequent presence of prominent ashes straddling the Gauss–Matuyama transition.

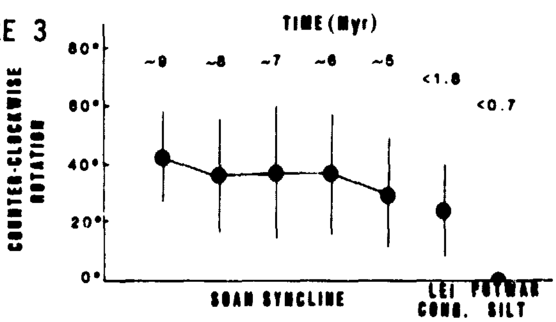
Sediment-accumulations rates and changes in these rates through time (from Johnson et al, 1982):

FIGURE 2



Post-depositional rotation of an area:

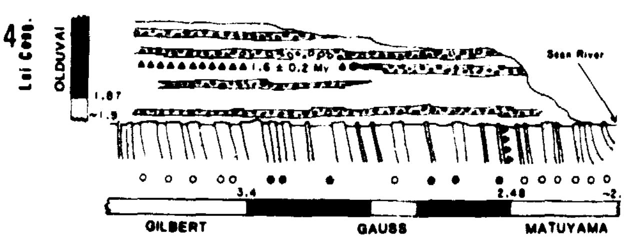
FIGURE 3



Post-depositional rotation of foredeep sediments in the vicinity of the Soan Syncline. Amount of rotation is based on the deviation of the mean orientation of the normal and reversed magnetic sites from a given time interval with respect to the theoretical north–south axial dipole. The chronologically constrained data indicate that up to 15° of counterclockwise rotation occurred between 9 and 2 Myr ago. However, the most rapid rotation of over 20° occurred between 1.8 Myr and the present, following the development of the Soan Syncline.

Rate and magnitude of uplift, erosion, and deformation of a stratified sequence:

FIGURE 4



The northern limb of the Soan Syncline, where nearly vertical strata of typical Siwalik molasse sediments are truncated and overlain by the generally underformed Lei conglomerate. Only the upper portion of >3,000 m of molasse sediments is shown. ▲, Enclosed volcanic ashes. The magnetostratigraphy[31] indicates that these strata encompass the Gauss chron and that the youngest preserved sediments extend into the lower Matuyama chron, probably to ~2.1 Myr. The overlying Lei conglomerate includes an ash dated at 1.6 ± 0.2 Myr (ref. 29) on the basis of which the normal-polarity magnetozone is interpreted as the Olduvai subchron. The base of the Lei conglomerate must predate the Olduvai and is interpreted as ~1.9 Myr. Thus, between 2.1 and 1.9 Myr ago, >3,000 m of uplift and erosion (mean minimum rate of 15 mm yr^{-1}) occurred as the Soan Syncline was strongly compressed in response to thrusting along the MBT.

Synthesis in time and space of the relationships between tectonic events and sedimentation within the adjacent basins. The timing of faulting and uplift events, the chronology of facies transitions, and paleocurrent observations form the basis for the synthesis depicted here:

FIGURE 5.

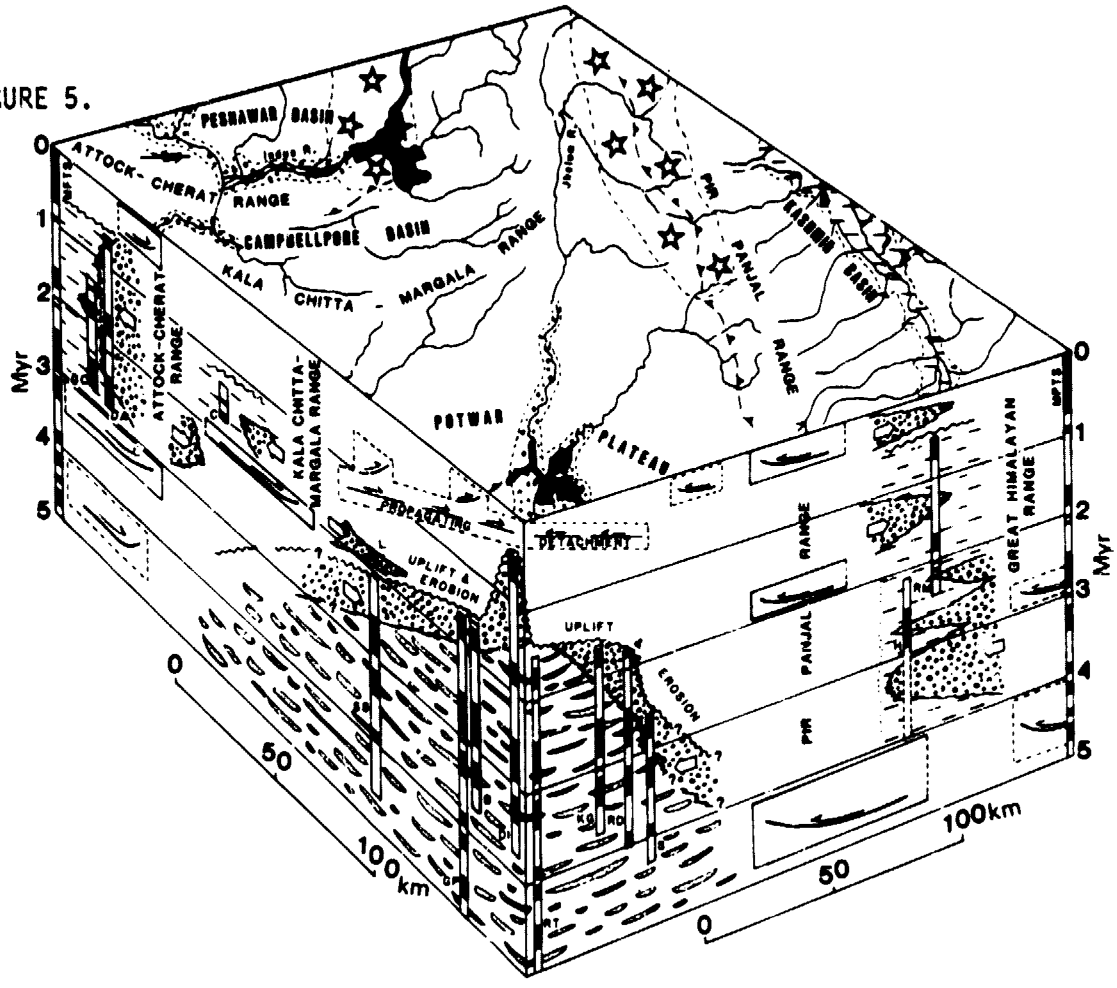


Fig. 6 Time–distance block diagram of the Himalayan foredeep and adjacent ranges in the vicinity of the North-west Syntaxis. The vertical dimension extends back to 5 Myr. The dated sequences described in this study and shown in Fig. 2 are depicted in their chronological range and are projected from their geographical location on to the transects defining the sides of the block. The abbreviations next to each magnetic column are as in Figs 1 and 2. Medial sections such as Sakrana (S) could be projected onto either face. The northeastern face is chosen here based on the affinities of the conglomerates at Sakrana with those from Rata–Dadial (RD) and Kas Guma (KG). For each of the stratigraphical sections, generalized depositional and facies relationships are shown in their proper chronological position (for example, the southward progradation of conglomerates from Sakrana across the eastern Potwar Plateau after 3 Myr). The intermontane basins are dominated by low-energy (largely lacustrine) facies punctuated by conglomeratic influxes. Two broad phases of molasse sedimentation across the Potwar Plateau are shown: a channel-and-floodplain interval succeeded by late-stage polymictic conglomerates. Large, open arrows indicate the prevailing palaeocurrent directions at different times. The boxes enclosing a thrust-fault symbol delineate both the spatial and chronological intervals over which the thrusts are interpreted to have been active. Dashed boxes show less well constrained periods of thrusting. On the left-hand panel, thrusting, folding and intermontane basin formation are seen to progress in a stepwise fashion from the Peshawar Basin to the south-east between 4 and 1 Myr ago. On the right-hand panel, three intervals of uplift in the vicinity of the Pir Panjal Range have defined the Kashmir Basin, controlled palaeocurrent patterns, and deformed the adjacent foredeep to the south-west. The surface of the block illustrates active, present-day processes. Deposition is largely restricted to the axial portions of the intermontane basins and narrow floodplains. Regions of high seismicity within 10–15 km of the surface[22] are shown by stars. Presently- or recently-active faults that break the surface seem to be associated with shallow seismicity.

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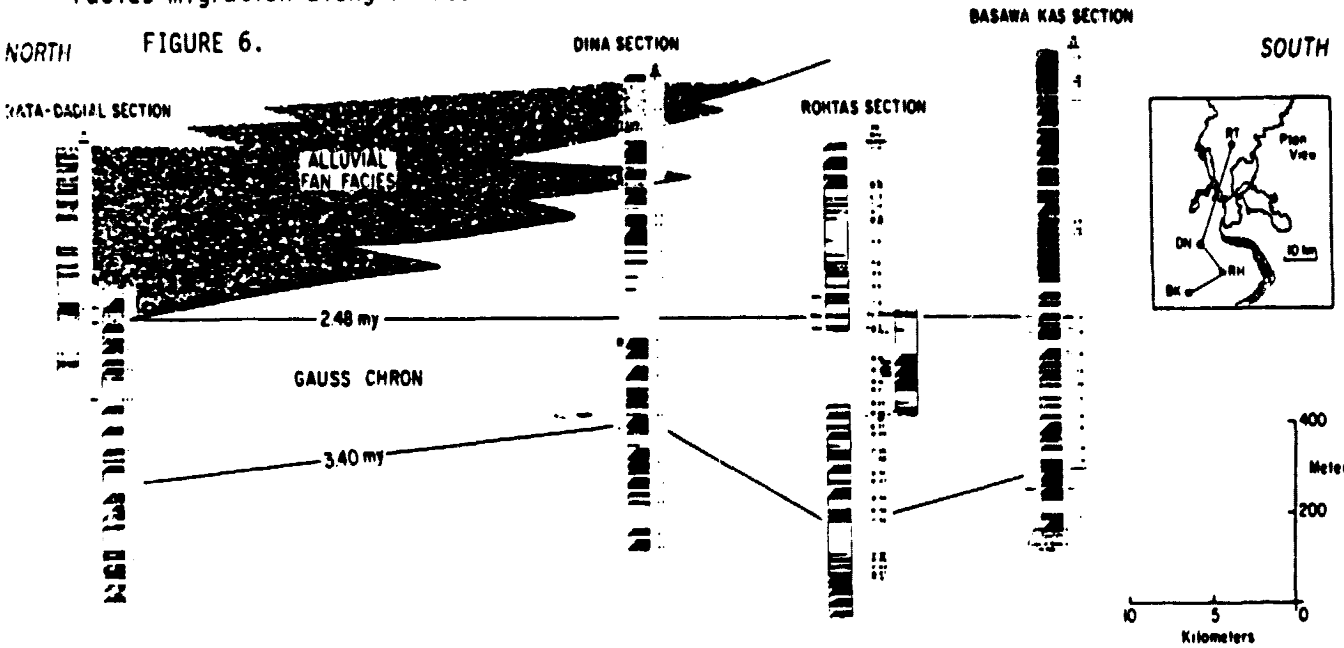
Facies migration along a dated transect (from Raynolds and Johnson, in press):

FIGURE 6.



Each of these figures illustrates an example of how detailed chronologies can be utilized in enhancing and refining models of basin analysis and tectonic deformation. From the geochronologist's point of view (particularly that of someone attempting magnetostratigraphic studies), one could ask, "How can remote sensing assist me in obtaining my goals?" I can only suggest some possibilities, some of which may not be practical at present. A key in magnetostratigraphic analysis is to identify the crucial sections that offer the most complete sequence and span the longest interval of time. As a mapping tool, remote sensing can help to locate these sections. It might also be able to answer questions concerning the make-up of the type sections. Do they contain a high proportion of mudstones or are they dominated by conglomerates? Certainly, remote sensing could discern whether or not there were red beds within the type section. Given the developing capability of remote sensing to identify mineral spectral signatures, could it differentiate between magnetite and hematite? Would the spectral signature vary as a function of grain size (hematite coatings=post-depositional remanence vs. detrital hematite=primary remanence)? Once chronologies have been developed within a series of section, remote sensing could be used to correlate lithofacies between sections. In the figure above, a conglomeratic facies is correlated over a distance of 50 km. The actual facies was not, however, physically traced over its entire distance, nor is it practical to do this for many correlations (it's too time consuming). Consequently, mapping of facies via remote sensing would be a very useful means of determining the facies relationships between dated sections. After a type section is identified, remote sensing could be useful for searching for and locating complete or nearly complete sections adjacent to structural discontinuities. This might enable dating of the type illustrated in figure 4, where the youngest and oldest preserved strata surrounding a deformational event have been dated.

Above, I have outlined just a few of the possible categories of useful information that might be obtainable through remote sensing studies and that would be directly applicable to absolute-dating studies based on magnetostratigraphy. Certainly there are other applications, but for now it would be ideal to be told, "The longest sections have been identified. They are dominated by mudstones and sandstones with minor limestones and conglomerates. Magnetite is abundant in nearly all portions of the sections, and hematite is a very minor factor!!"

N86-10603

TERTIARY AND QUATERNARY RESEARCH WITH REMOTE SENSING METHODS

James E. Conel

Introduction

Analysis of the stratigraphic section is a fundamental aspect of the geologic study of sedimentary basins. Stratigraphic analysis of post-Cretaceous rocks in the Wind River Basin encounters problems of a distinctly different character from those involved in studying the pre-Cretaceous section. The interior of the basin is predominantly covered by Tertiary and Quaternary sediments. These rocks, except on the basin margin to the north, are mostly flat lying or gently dipping. The Tertiary section consists of sandstones, siltstones, and tuffaceous sediments, some variegated, but in general poorly bedded and of great lithologic similarity. The Quaternary sediments consist of terrace, fan, and debris tongue deposits, unconsolidated alluvium occupying the bottoms of modern watercourses, deposits of eolian origin and tufa. Terrace and fan deposits are compositionally diverse and reflect the lithologic diversity of the source terranes.

This discussion will focus on problems encountered in mapping the Quaternary section using remote sensing methods. The Quaternary record is more accessible. These deposits lie atop the Tertiary rocks, and the present landscape is often dominated by landforms of Quaternary origin. Analysis of the Tertiary section will be the object of subsequent investigations.

Significance of Quaternary in Basin Research

Rivers cut across diverse continental environments and have proved to be of special value in studying Quaternary environmental change (Baker, 1983). Rivers of the Pleistocene were subject to significant climatic fluctuations, but a divergence of opinion exists on the problem of terrace formation in separating climatic influences and nonclimatic factors such as stream capture (and tectonism and/or isostatic uplift). Morrison (1968) for example doubts that cycles of fluvial erosion, deposition, and stability are reliable indicators of glacial-interglacial cycles. Palmquist (1983) studied the Bighorn River and its tributaries and found both in- and out-of-phase relationships for eastern and western tributaries. He concluded that not all climatic cycles of the Pleistocene were capable of generating a terrace cycle.

In arid southwest environments the significance of alluvial fans for climatic conditions remains controversial. Thus Lustig (1965), in Deep Springs Valley, assigned the construction of alluvial fans to past episodes of wetness, and the current period of fan incision to onset of modern aridity. Hunt and Mabey (1966) on the other hand relate fan growth in Death Valley to the inception of drier conditions after a wet phase of preparatory weathering. Denny (1965) regards erosion and deposition to be parts of the steady state system that generates fans and thus discounts any connection with environmental conditions to explain alterations of process.

Study of the Quaternary fluvial and alluvial chronology of the Wind River Basin may prove to be especially significant in providing a relationship between river terrace formation, glacial and interglacial cycles, and alluvial fan development, all within the limited physiographic province comprising the basin. In broad terms the physiography of the northwestern part of the basin is characterized by the presence of at least 13 remnant terraces along the Wind River and its tributaries south of Cottonwood Creek (Morris, et al., 1959), and by alluvial fans, most incised, issuing from canyons along the Owl Creek Mountains. A similar relationship extends eastward from Boysen Reservoir. North of Badwater Creek, alluvial fans and long debris tongues, often expressed in reversed topography, and occupying multiple step-like pediment surfaces, characterize the physiography along the East Owl Creek Mountain front, while to the south are found a series of broad terraces correlating roughly with those identified by Morris et al. to the west and north of Wind River.

Nature of Remote Sensing Observations

Satellite and aircraft multispectral scanner systems record radiance of solar origin that has been transmitted and scattered by the Earth's atmosphere and directly reflected from the surface (0.4 - 2.5 micron region), or absorbed by the surface and reemitted as thermal radiation (8 - 14 micron region). In the visible and near-infrared region the parameter of interest is the (predominantly) bi-directional spectral reflectance, and in the thermal infrared region it is (predominantly) hemispherical-directional emittance. Satellite scanner systems such as the Landsat TM record radiance over bandpasses on the order of a few tenths of microns in width. With such data it is possible to "resolve" crudely major absorption features in the reflectance spectra of surface materials such as chlorophyll and water absorptions in plants, and ferric iron absorptions in surface pigments such as hematite and limonite. The surface resolution is on the order of thirty meters. On the other hand airborne spectrometer systems such as AIS provide spectral resolution on the order of a few nanometers in the region 1.1 - 2.5 microns. This spectral resolution is sufficient to permit identification of clay minerals (kaolinite, montmorillonite, etc.), the identification of calcite, dolomite, and gypsum, and possibly detection of such mineral phases as chlorite and biotite. The surface resolution is on the order of ten meters. In the thermal infrared, the detailed location of emission features is related to presence of lattice vibrational absorptions of minerals comprising the surface (plant cover tends to behave as a black body), and the degree of Si-O polymerization. The most characteristic phase is quartz, and quartz-rich rocks are easily discriminated from other cover types not containing this mineral. The airborne Thermal Infrared Mapping Spectrometer (TIMS) provides observations with bandwidth on the order of 0.2 microns in six bands throughout the thermal infrared region. The surface resolution typical of aircraft observations is about 15 meters. Despite numerous difficulties surrounding the quantitative interpretation of thermal emission data, thermal imagery proves useful for discrimination of rock types, and possibly differing physical states of the same rock type (i.e., solid outcrop vs talus or colluvium). With the possible exception of quartz, it cannot yet be said that rock or mineral "identification" is possible from these observations. This development must await implementation of more quantitative methods of data analysis.

Likely Contributions and Drawbacks of Remote Sensing Imagery

The observations described provide after calibration accurate (<1%) measures of surface spectral reflectance or emittance. These observations may be used for determination of rock type, discrimination of one lithologic type from another and for correlation of lithologic units from place to place. These photometrically precise spectral observations may also be combined to provide principal components or canonical variates, which act to compress the information present in the spectrum into a few variables suitable for image display. These new statistically significant variables are useful in classification schemes for correlation or discrimination studies. The presentation of spectral reflectance (or emittance) information in pictorial format as images provides a convenient (and in the case of TM) geometrically accurate basis for the plotting and measurement of the distribution of Quaternary deposits.

The mapping and correlation of terrace and alluvial deposits, and establishment of sequences of events from one place to another within and between drainage systems is ordinarily accomplished using stereoscopic aerial photographs, topographic maps, and field observations. Accurate topographic information is required for the construction of cross sections and longitudinal profiles. Since only under exceptional circumstances is stereoscopic coverage obtainable with image data, either satellite or aircraft, all quantitative studies of terrace sequences, correlations, and other details of the geomorphology and structure require that these additional sources of data be employed. For actual solution of the geologic problems described here these additional data sources may be of dominant importance.

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Multisensor Data Integration Techniques

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The availability of data from sensors operating in several different wavelength regions has led to the development of new techniques and strategies for both data management and image analysis. Work is ongoing to develop computer techniques for analysis of integrated data sets. These techniques include coregistration of multisensor images, rectification of radar images in areas of topographic relief to ensure pixel to pixel registration with planimetric data sets, calibration of data so that signatures can be applied to remote areas, normalization of data acquired with disparate sensors and determination of extended spectral signatures of surface units. In addition, software is being developed to analyze coregistered digital terrain and image data so that automated stratigraphic and structural analyses can be performed. These software procedures include: strike and dip determination, terrain profile generation, stratigraphic column generation, stratigraphic thickness measurements, structural cross-section generation, and creation of 3-D block diagrams.

These techniques have been applied to coregistered Landsat 4 Thematic Mapper (TM), Thermal Infrared Multispectral Scanner (TIMS), and multipolarization synthetic aperture radar (SAR) data of the Wind River Basin in Wyoming. This type of approach exploits the unique photogeologic qualities and spectral information of independently interpreted and coregistered images for stratigraphic analysis. Photogeologic interpretation of 1:24,000 scale TM images can be used with 7 1/2′ topographic maps to construct stratigraphic columns. Independent spectral interpretation of AIS, TIMS and SAR data yields mineralogical and textural information that can be incorporated into TM-derived stratigraphic columns.

The integration of data from multiple sources requires advanced techniques for data management. A management system is being developed under the Pilot Land Data System (PLDS), a program sponsored by the National Aeronautics and Space Administration (NASA) to improve the ability of NASA and NASA-sponsored scientists to conduct land-related research. This type of management service will greatly improve our capabilities to locate, access, process, analyze, and interchange remotely sensed and other land science data.

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POSITION PAPER

Tim Gubbels
January 9, 1985

The northern boundary of the Wind River basin is complex; the western and central portions of this basin rim are occupied by the E-W trending Owl Creek uplift, while the eastern part of this basin rim is occupied by the N-S trending Bighorn Mountains. The juncture between the Owl Creek Mountains and the Bighorn Mountains is a relatively continuous convex eastward uplift. This physiographic continuity is misleading, since it is known that the Owl Creek Mountains were defined and uplifted prior to the development of the southern Bighorn (Love et. al., 1963). In an area east of Thermopolis, Wyoming, on the north Flank of the Owl Creek Mountains, structural elements of both the Bighorn and Owl Creek uplifts are displayed. This region is known as the Red Hole area and includes the Wildhorse Butte, Red Springs and East Warm Springs anticlines. The East Warm Springs anticline strikes generally East-West, typical of folds in the north-central part of the Owl Creek Mountains, while the Wildhorse Butte and Red Springs anticlines strike northwesterly, as do most of the asymmetric anticlinal folds present in the southwest corner of the Bighorn basin. Exposures in the area are excellent, and a rather unique structural configuration is displayed.

I plan to use the Thematic Mapper (TM) data, Thermal Infrared Multispectral Scanner (TIMS) data, and Radar data, in conjunction with available subsurface data and detailed field mapping to make an in-depth structural analysis of the area. My goal is to decipher the tectonic evolution of this part of the Owl Creek Mountains and relate this to the regional structural configuration of the Bighorn and Wind River basins. Important questions in this light include the relative timing of the uplifts, the history of the stress regime, as well as the nature of the "piggyback" structural relationships of this area to the Owl Creek tectonic package. I feel that, contained within the Red Hole area, is key evidence pertaining to these questions.

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N86-10605 D6

PREPARED FOR: WORKSHOP ON GEOLOGIC APPLICATIONS OF REMOTE SENSING TO THE STUDY OF SEDIMENTARY BASINS, JANUARY 10-11, 1985

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Remote sensing data in the next decade should provide increasingly better information for geologic applications, especially with the availability of Landsat TM data and, in the future, data from systems such as AIS and TIMS. The distribution, geometry, and composition of rock units contain the record of the history of the crust and a large proportion of our nonrenewable resources. The degree to which rock units have been mapped throughout the Earth varies considerably depending upon the accessibility and exposure of the terrain. Analyses of remote sensing data will enhance our ability to map the poorly known areas. In arid and semi-arid regions rock units can be mapped directly. However, a large fraction of the land areas is covered by vegetation, and rock units cannot be seen directly. Thus, it is important to understand the geologic control on vegetation in order to map rock units by remote sensing methods in vegetated regions. For example, we have been analyzing TM data covering oak-hickory forests in southern Missouri. We find that there is a control on the infrared reflectance (bands 4, 5, and 7 of the TM) of the forests that correlates with rock and soil types. During the growing season soils with low water retention capacities correlate with high infrared (band 4, lesser in bands 5, 7) signatures.

Analysis of remote sensing data should be driven by a set of science objectives. The types of science questions that are being addressed will determine the types of data to be used and how to properly process and display the data. Using this approach, we are studying a metamorphic core complex called the Meatiq located in the Eastern Desert of Egypt. The dome provides exposure of most of the rock units of the Arabian-Nubian Precambrian Shield. The dome bears many resemblances to Cordilleran metamorphic complexes. We are using Landsat TM data to improve on reconnaissance maps of the dome. We are also interpreting the remote sensing data in the context of field observations, petrographic, and chemical analysis of rock units in the dome, in order to map similar domes in the Eastern Desert from TM data. Mapping projects such as the one just described will help constrain the geologic evolution of the Arabian-Nubian Shield. Two particular hypotheses that we hope to test for the development of the shield are: 1) closure of a proto-Red Sea; or 2) accretion of a primitive island arc system onto the shield.

Making quantitative estimates of surface composition from remote sensing data will require new data analysis methodologies. One approach that we are pursuing is the use of various curve fitting techniques in construction of spectral reflectance estimates from TM data. The TM sensor has obvious problems with spectral undersampling, but we have found that the technique can provide useful information on the shapes of reflectance curves that can be used to map spectral variability from place to place. This approach is providing experience in how to handle data from imaging spectrometers (e.g., SISEX, HIRIS, VIMS) that may provide data in the next decade. These systems would produce orders of magnitude more data than present systems.

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Position paper - MARY HARRIS - University of Wyoming
Workshop on geologic applications of remote sensing to the study of sedimentary basins

January 1985, Denver

I am a graduate student with a background in geology, botany, remote sensing, geochemistry and tectonics. I plan to do a botanical - geological study of JPL's Deadman Butte subarea with the goal of developing remote sensing techniques for geologic mapping using plant/rock relationships.

Botanical responses to metal anomalies in soil and rock are well documented and are currently being studied (for example the work at Goddard Space Flight Center and the Department of Botany, University of Maryland on deciduous forests in Virginia). Studies of how plants respond to other geologic variables and in particular how they respond in semiarid environments similar to the Wind River Basin are scarce to nonexistent. I intend to use the TM, TIMS, AIS and other remotely sensed data available for the Deadman Butte area in conjunction with my own botanical ground truth to try to isolate the contribution of the vegetation to the remote sensing data in order to use it to enhance geologic units being mapped, either by augmenting a particularly useful characteristic vegetation signal or by subtracting out a noncharacteristic vegetation signal, allowing the information from the rock and soil to dominate.

I will begin by assessing, on a formation-by-formation basis, what species are present, and in what proportions. I will then try to relate this information to the remote sensing data using image processing techniques such as ratioing of spectral bands (vegetation indicies), and principal component analysis (Hotelling transformation). Arid and semiarid ecosystems are different from those in wetter environments: there is less species diversity and less interspecies competition. Adaptation is often accomplished by changes in morphology or changes in timing of plant seasonal functions. Therefore, these two variables must also be considered in the botanical response to varying geologic conditions.

It is hoped that techniques will be developed by this approach that will be adaptable for use in other geographic areas; i.e., that some basic plant ecophysiological responses to geologic variables, that can be detected by remote sensing, will be of value in other types of ecosystems.

What I hope will come out of this workshop, as far as my own project is concerned, is a feeling for parameters other than classic formational boundaries, that are of interest to those of you who are mapping. Stratigraphers may need to study lateral grain-size or mineralogical changes within a formation. Structural geologists may be interested in brecciated fault zones or areas of pervasive microstructures that may be highlighted by vegetation differences. Let me know what you are looking for. I want to develop techniques that are useful to you.

Position Paper
Sam Johnson, U.S.G.S., Denver

The U.S.G.S. has just initiated a new research program titled "Evolution of Sedimentary Basins." I am one of a group of geologists that will pursue studies in the Uinta-Piceance Basin, a rectangular 170,000 km^2 area that includes the Paleogene Uinta, Piceance Creek, and Sand Wash basins, and surrounding uplifts. This area has a complex tectonic and sedimentary history. Late Paleozoic to Paleogene strata formed in several discrete basins and are host to numerous important commodities. Mississippian carbonates largely formed on a stable shelf and shelf margin and locally contain metallic ores. This shelf and shelf margin were partially fragmented in the Pennsylvanian and Permian into discrete fault-bounded basins. Pennsylvanian and Permian strata include a range of marine and nonmarine siliciclastics, carbonates, and evaporites, and are host to oil and gas, uranium, and potash. A relatively stable continental platform characterized the Uinta-Piceance region in the Triassic and Early Jurassic. Nonmarine and marginal marine siliciclastics deposited on this platform contain oil and gas, tar sandstones, and uranium deposits. During the Late Jurassic and Cretaceous, the Uinta-Piceance Basin formed a portion of a foreland basin that extended from the Gulf of Mexico to Arctic Canada and was bounded on the west by the western overthrust belt. Siliciclastics deposited in this foreland basin host oil and gas, and coal. Latest Cretaceous to Paleogene fragmentation of the foreland basin by Laramide uplifts led to formation of the internally-drained Uinta and Piceance Creek basins. Siliciclastic and carbonate rocks deposited in these restricted basins contain some of the worlds largest accumulations of oil and gas in nonmarine rocks, greater than 90% of the country's exploitable oil shale, tar sandstones, coal, and minor amounts of uranium.

Efficient exploration and development of sediment-hosted resources in the Uinta-Piceance Basin is based on proper understanding of sedimentary basin evolution. The goal of the Evolution of Sedimentary Basins Program is to improve this understanding through integrated stratigraphic, sedimentologic, structural, and geochemical studies. Data and interpretations generated in these studies will provide the basis for paleogeographic reconstruction.

My main expertise is in stratigraphy and sedimentology, so I am most interested in how remote sensing could be used as a tool in stratigraphic and sedimentologic studies in the Uinta-Piceance Basin. Depending on the quality and resolution of remote sensing data at small scales (1:24,000 and smaller), remote sensing data could be an important tool in extending a field data base over large areas. For facies analysis, for example, the ability to recognize subtle vertical and lateral lithologic changes would be most important. Similarly, the ability to distinguish some of these characteristics in vegetated areas would be extremely useful. The utility of using remote sensing data in facies analysis would strongly depend on the expense of obtaining and processing raw data.

Because sedimentation in the Uinta-Piceance Basin was strongly affected by regional tectonics and faulting, analysis of major and minor lineaments has potential for unravelling complex basin histories. Integrating lineament data with sedimentary facies data obtained by remote sensing and in the field could provide important information concerning the histories of basin margins and the relationships between sedimentation and tectonics.

N86-10606

REMOTE STRATIGRAPHIC AND STRUCTURAL ANALYSIS: MULTISENSOR RESULTS IN THE WIND RIVER/BIGHORN BASIN AREA, WYOMING

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Inadequate spatial resolution and spectral coverage have limited the utility of multispectral image data for detailed geologic studies in mature exploration provinces. Previous exploration applications have therefore emphasized reconnaissance structural mapping, lineament analysis and detection of so-called "tonal anomalies". New sensor systems, available since 1982, now provide improved spatial resolution, spectral coverage and geometric fidelity. Results of a feasibility study conducted in a typical North American foreland basin demonstrate that data acquired by these new systems can complement conventional geological and geophysical data for detailed stratigraphic and structural studies in mature oil and gas provinces.

Landsat Thematic Mapper (TM), Airborne Imaging Spectrometer (AIS) and Thermal Infrared Multispectral Scanner (TIMS) data were acquired in the Wind River/Bighorn Basin area of central Wyoming. Combined image processing, photogeologic and spectral analysis methods were used to: 1) measure stratigraphic sections, 2) correlate strata, 3) identify mineralogical facies, and 4) construct geologic maps and cross sections at scales of 1:250,000 and 1:24,000.

Preliminary photogeologic interpretation of a 1:250,000 scale TM image identified an appropriate type locality for constructing an image derived stratigraphic column. This type locality encompasses exposures of homoclinal strata in the Deadman Butte area of the Casper Arch, eastern Wind River Basin. A 1:24,000, 512X512 pixel TM image of the Deadman Butte area provided a photogeologic base for mapping spectral, textural and geomorphically defined photogeologic horizons. The TM image geometrically matched U.S.G.S. 7 1/2' topographic maps. Thus, standard geologic map interpretation methods could be used to construct a stratigraphic column incorporating spectral characteristics, true stratigraphic thickness and resistance of the photogeologic units. This column was correlated with a conventional surface section measured 6 miles to the west. Thus, the 38 image units were assigned to 11 formations ranging in age from the Permian Phosphoria to the Cretaceous Cody Shale. The Deadman Butte TM stratigraphic column was also correlated with a similarly constructed column from a structurally complex area in the southern Bighorn Basin and also with well logs from both the Wind River and Bighorn Basin.

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Spectral interpretation of AIS and TIMS data acquired in the Deadman Butte area provided mineralogical information for the TM defined units. Thus the stratigraphic distribution of dolomite (dolostones of the Phosphoria Formation), gypsum (anhydrites of the Dinwoody/Chugwater Formation transition), calcite (limestones of the Alcova Member), montmorillonite (bentonites of the Mowry Shale and Frontier Formations), and quartz (orthoquartzites throughout the section) were incorporated into the stratigraphic column. These results demonstrate the feasibility of using new multisensor data for correlation of strata and for isopach and facies mapping. This stratigraphic information can be integrated with conventional surface, borehole and geophysical data in searches for stratigraphic traps.

Detailed structural interpretation of a 1:24,000, 512X512 pixel TM image of the Thermopolis Anticline area, southern Bighorn Basin, demonstrates the existence of a previously unreported thrust fault and an associated northwest trending asymmetric anticline. Photointerpretations indicate that the steeper southwestern limb of the anticline is vertical to overturned. A TM-derived cross section incorporating well log data confirms fold geometry and concave up nature of the fault plane. Application of structural models that assume vertical uplift or drape folding result in imbalanced cross sections; volumetric and bed length conservation can only be accomplished with a thrust fault model. Regional 1:250,000 structural interpretations reveal that similar asymmetric folds and associated thrust faults are typical of the southern Bighorn/northwestern Wind River foreland basin region. These results support a compressional tectonic model for Laramide deformation in the area, and identify numerous structural prospects beneath the thrust faulted southwestern limbs of asymmetric anticlines in the southern Bighorn basin.

*Performed under contract with NASA.

N86-10607

Structural Mapping of Folded Sedimentary Environments from Satellite Images: An Example from Central Asia

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There are a few types of geologic terrain that are particularly conducive to the translation from satellite image to geologic map. The best conditions occur in arid areas where large, open folds affect sedimentary rock units that have a few, regionally continuous and erosionally resistant marker beds. These conditions prevail in the Tadjik Depression, in Soviet Central Asia, where, in the absence of existing geologic or topographic maps, we have used an enhanced[2] Landsat MSS image in combination with field data to produce a 1:250000 geologic map of the Vakhsh fold-and-thrust belt and adjacent autochthon (Leith and Alvarez, 1985).[1]

It is crucial, when undertaking the construction of any geologic map, to recognize the key or *marker* beds or contacts that can be traced across the map area for large distances--either on the ground, on an aerial photograph or on a satellite image. In the case of Landsat, the size of a marker bed is, optimally, near the scale of the resolution of the sensor (79 m for Landsat 1,-2, and -3 MSS imagery, 30 m for TM imagery), and the accuracy of contacts mapped will depend on how accurately the marker beds have been distinguished. Proceeding in this manner (fig. 1), we were able to define and trace erosionally resistant marker beds across the 170 km length of the Vakhsh fold-and-thrust belt. In addition, in order to accurately represent the patterns of color and relief on the image as structural information, image mapping was complemented by field study. This was necessary to provide lithologic detail, to determine the nature of unconformities, and, in the absence of detailed topographic data, to obtain accurate structural dips. We stress that without the ground information, the quality of the structural mapping suffers significantly.

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1. Leith, W. & W. Alvarez, "Structure of the Vakhsh fold and thrust belt, Tadjik SSR: Geologic mapping on a Landsat image base," *Bull. Geol. Soc. Am.* (in press) (1984).

2. In addition to standard image enhancement procedures such as destriping and contrast-stretching, a 101x101 (pixel) spatial filter (a subtractive boxcar filter, representing an area approximately 8000 m on a side) was passed through the digital data. Such a filter enhances features that are less than about half of its size. In this case, the use of this filter was to more clearly bring out the fine structural detail of the imaged area.

The following structural conclusions were reached as a result of this mapping: 1) Deformation of the Cretaceous and Tertiary strata of the fold-and-thrust belt is, in the central Tadjik Depression, conspicuously absent north of a buried basement fault that marks the hinge-zone of the Late Mesozoic passive margin. But, in the eastern half of the Depression, thrusting has moved coherent sheets northward, over the block fault -- these sheets now lie flat atop the autochthon to the north; 2) the crustal structure inherited from the Mesozoic extensional phase has strongly influenced the Late Cenozoic pattern of deformation, producing the fold-and-thrust belt that is markedly asymmetric; 3) the development of the thrust system has included the progressive overlapping of thrusts: the later thrusts apparently formed internal to the older thrusts, and subsequently overrode them.

The technique is most applicable to folded and faulted sedimentary rocks in arid environments, where the outcrop morphology or spectral reflectance distribution of the section lends itself to division into mapping units resolvable by the satellite sensor. With greater spatial resolution (e.g., TM imagery) and the addition of detailed topography, reliance on fieldwork may be further reduced.

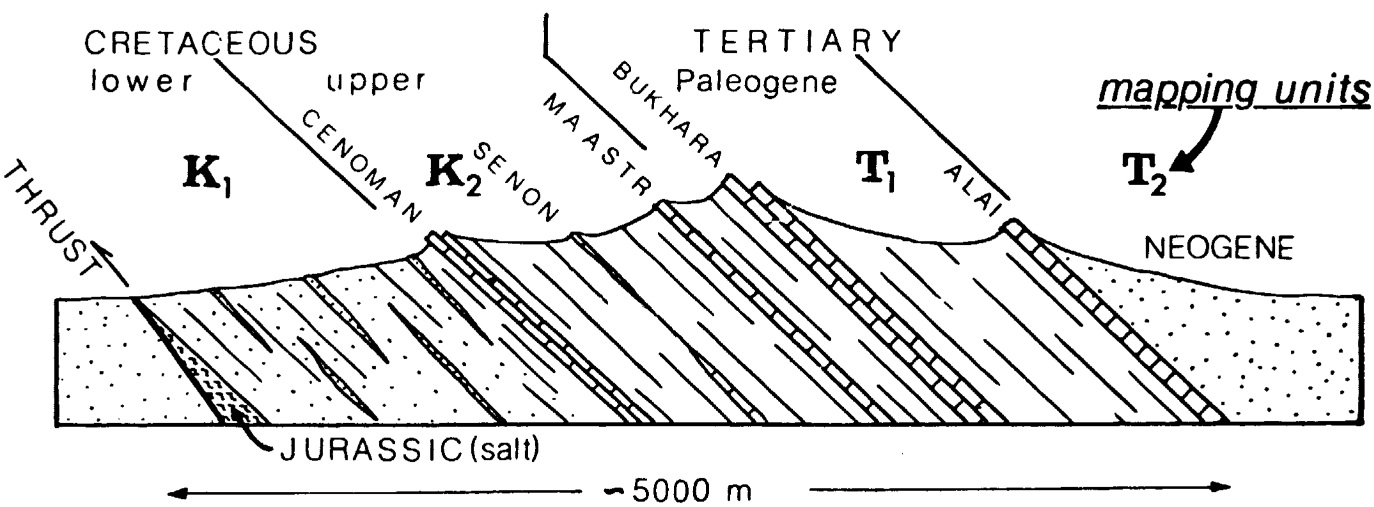

Figure : Stratigraphy and outcrop morphology of the sedimentary rocks of the Tadjik Depression. The structure seen on the imagery is punctuated by the limestones of the Cenomanian, Bukhara and Alai subgroups, which outcrop as distinctly erosion-resistant beds. This cross-section shows that these may be used to divide the section into units mappable at the scale of resolution of the Landsat sensor.

N86-10608 D9

FORELAND BASIN STRUCTURES AND REMOTE SENSING

Earnest D. Paylor/JPL

One of the important facets of sedimentary basin evolution is the development of structural features within the basin. The diversity of styles of basin structures observed in the geologic record stems in part from the plate tectonic setting of the basin through time and the related processes of subsidence, sedimentation, and tectonism. These structures are targets of exploration, therefore, an understanding of their development as controlled by the basin's evolution is of prime importance.

Rocky Mountain foreland basins are somewhat unique in that the basins may exhibit a variety of structural styles. For decades, geologists have debated the mechanics of formation of these foreland structures. It is generally agreed that shortening has occurred in the foreland basement but the cause is controversial: vertical vs. compressional (horizontal) tectonics. Even when shortening is attributed to compression, the attitude (dip) of the fault plane and whether the horizontal or vertical component of movement is dominant is unconstrained. The controversy is difficult to resolve from surface data alone due to the variety of possible interpretations. Borehole and geophysical data provide constraints on the geometry and hence the mechanics of formation of these structures. Recent deep drilling data and seismic data in the foreland region support a compressional (low angle thrust) model of deformation. Thus, subthrust exploration in these areas may become an important future activity. Detailed surface mapping and geologic modeling are still needed to constrain subsurface interpretations. In many areas of the Wind River and Bighorn basins detailed geologic maps do not exist. State-of-the-art remote sensing data could potentially provide an efficient means of mapping surface geology.

Inadequate spatial resolution, spectral coverage, and lack of geometric fidelity have limited the use of satellite remote sensing data for detailed geologic studies. Previous applications of these data have concentrated on regional studies such as lineament analyses, delineation of "anomalies" (color, hazy, vegetation, etc.), detection of areas of mineralization, and reconnaissance stratigraphic and structural mapping. State-of-the-art systems now provide geometrically correct data at 30 meter pixel size and increased spectral coverage, capable of more detailed geologic analyses. These data can be photographically enlarged to 1:24,000 scale and combined with 7 1/2' USGS topographic quads to provide an excellent base map for geologic interpretations. At this enlarged scale, 3-point problem solutions provide measurements of attitude of photogeologic units that enable construction of stratigraphic columns, cross sections, down-plunge projections, stereographic projections, etc. These new remote sensing data and techniques complement conventional methods of detailed geologic structural analysis.

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POSITION PAPER ON THE SAN JUAN BASIN

by
Jennie Ridgley

The U.S. Geological Survey has recently initiated a new research program that will examine the evolution of sedimentary basins. This program, using the basin analysis approach, is a multidisciplinary study that will focus on the structural and sedimentologic evolution of individual basins. Emphasis of this program will be on the reconstruction of the areal extent of an individual basin with time, looking at the tectonic, sedimentologic, and diagenetic processes and histories as they affect the location and concentration of solid and liquid fuel and metallic and non-metallic resources in the basin and bounding uplift rocks.

The San Juan Basin, located in Northwest New Mexico and southern Colorado, is one of the basins to be studied under this program. Although numerous geologic studies have been conducted in this basin, there has not been a coordinated effort to integrate all this data, using a basin-wide approach. One of the principal studies, to be conducted, will be to examine the structural evolution of the basin, with time. We are, therefore, interested in the role of plate tectonics in the changing configuration of the basin.

The present-day structural configuration of the San Juan Basin is related to tectonic events that began in Late Cretaceous time (Laramide) and continued well into the mid-Tertiary (time of Rio Grande Rift formation). From past geologic studies, we know that the San Juan Basin was the site of deposition, beginning in the Cambrian, and that present bounding uplifts were the site of periodically positive elements throughout the geologic past. However, throughout most of the areal extent of the basin, Cambrian-Mississippian age rocks have largely, but not entirely, been removed. Reasons for removal and tectonic events that may have been involved are not well understood. Beginning with the Pennsylvanian, thick sequences of sediments were deposited. From isopach maps, it would appear that the position of the main axis of sedimentation (perhaps a pseudo-basin axis) shifted from one geologic time period to the next. Exact configuration of the various "basin" extents is unknown, but during certain geologic periods the "basins" may have been open ended in one or more directions. Tectonic controls (especially those that relate to plate tectonics) on the configuration of these "basins" are poorly understood.

In order to understand the changing structural configuration of the basin with time, we will be examining a large amount of seismic, Landsat MSS, and geologic data. Studies using Landsat MSS imagery to map and analyze linear features in the San Juan Basin and surrounding basin margins are largely completed. Dan Knepper will be reporting on the results of this study. We are presently examining the seismic data and plan to integrate interpretation of this data with lineament, gravity, and magnetics data that have been generated. Ultimately these interpretations will be integrated with lithologic, diagenetic, and facies distribution data for the various time periods.

One key question is what additional remote sensing studies should or could be done? How valuable would mapping lithologies by remote sensing be in this area? Large areas of the San Juan Basin are presently mapped; little additional mapping is scheduled for this program. If the resolution of the Landsat imagery is such that individual features can be seen at the scale of a 7½ quadrangle, then perhaps this type of data would be useful to the study. However, the average geologist does not have the training to reduce the data himself. Would the cost of obtaining these data in a form that the geologists could use be worth it?

Several additional questions that are concerned with the discrimination of lithology, using Landsat MSS data, come to mind. In largely sandstone sequences can Landsat MSS derived imagery discriminate between sandstones within formation members and between formations? In the abstract by Lang and others, it is mentioned that spectral interpretation of AIS and TMS data was used to provide mineralogical information. I can understand the interpretation of dolomite (dolostone), calcite (limestone), and gypsum because essentially you are dealing with monomineralic rocks. Perhaps the same would be true for discriminating montmorillonite (bentonite) or silica (orthoquartzite), if the rocks are essentially monominerallic. How good is this technique for discriminating minerals in polyminerallic rocks (sandstones, mudstones, metamorphic or igneous rocks, etc).? What kinds of clay minerals can be identified with this technique and what proportions need to be present before the technique is accurate? In polyminerallic rocks, such as sandstone, what proportions of quartz, feldspar, etc. need to be present in order to identify them? Can zeolite horizons be mapped or identified? Can tuffaceous units be mapped or identified? What is the limiting thickness, i.e. minimum thickness, and areal extent of a rock unit before this technique can provide valid or useful information? Can any of the Landsat spectral data see through vegetation, like SLAR, to produce images free of vegetation so that structural features are enhanced?

N86-10609

PALEOGENE VERTEBRATE PALEONTOLOGY, GEOLOGY AND REMOTE SENSING IN THE WIND RIVER BASIN.

Richard K. Stucky and Leonard Krishtalka, Section of Vertebrate Fossils, Carnegie Museum of Natural History, Pittsburgh, PA.

Since 1880, paleontologists have intensively explored the Wind River and Bighorn basins of Wyoming for fossil vertebrates. Although the rocks in these basins have produced fossil vertebrates ranging in age from the Jurassic through the Miocene, most fossils have come from Paleocene and Eocene strata. Parts of these strata produce abundant and diverse fossil mammal faunas which are used as the "type faunas" for the Land Mammal Ages (LMA) and Subages (LMS) of the latest Paleocene and early Eocene terrestrial deposits of North America - In the Bighorn Basin: the Clarkforkian LMA (latest Paleocene) and two subages of the Wasatchian LMA (early Eocene), the Sandcouleean and Graybullian LMS (early and middle Wasatchian); in the Wind River Basin: the Lysitean and Lostcabinian LMS (late and latest Wasatchian). Diverse faunas from most of the Paleocene and Eocene are, however, well represented in the two basins.

Paleontologist from the Carnegie Museum of Natural History began systematic explorations in the early 1960's in the northeastern corner of the Wind River Basin, specifically in the Badwater Creek, Alkali Creek and Red Creek-Deadman Butte areas. This work has primarily involved systematic paleontology but in recent years has also included geologic mapping and sedimentologic and stratigraphic studies. The major purpose of these studies has been to develop a complete geologic and biologic context for studying the patterns of evolution and ecology among the fossil vertebrate faunas. In the northeastern Wind River Basin, faunas of late Paleocene to middle Oligocene age have been documented. Several biostratigraphic zones have been defined in the Wind River Formation and work now in progress will define additional zones. It appears that the late Paleocene and all of the Eocene can be more finely divided by these biostratigraphic zones in the Wind River Basin than by LMAs and LMSs.

Biostratigraphic and lithostratigraphic studies have been used to correlate different events in the geologic evolution of the northeastern part of the Wind River Basin and have suggested several conclusions, for example (speculating with some wreckless abandon): 1) laterally equivalent exposures of the Lysite Member from Cedar Ridge to Bridger Creek show a gradation in lithology from interbedded boulder conglomerates and sandstones to interbedded lenticular sandstones and mudstones to interbedded carbonaceous shales, coals and tabular sandstones. This gradation suggests a shift from alluvial fan to braided stream to paludal or lacustrine sedimentary environments during the late early Eocene; 2) the Lysite and Lost Cabin members of the Wind River Formation are in fault contact in the Bridger Creek area and may intertongue to the east along Cedar Ridge; 3) during Lostcabinian time (latest early Eocene) tectonic activity was more intense in the Badwater Creek area than in the Deadman Butte area (vicinity of the Casper Arch) as reflected by different depositional facies; and 4) parts of the so-called Green and Brown Member in the Badwater Creek area (Tourtelot, 1957), the Middle (?) Eocene Volcaniclastic unit in the Red Creek area (Stucky, 1984), and the Lower Sequence (?Unit 24) of the Eocene rocks at Hawks Butte in the Lysite Mountain area (Bay, 1969) are biostratigraphic and lithostratigraphic equivalents; and 5) number (4) above with the presence of a similar sequence of strata in the Beaver Divide area (southern Wind River Basin), and remnant Oligocene deposits in these areas suggest that these deposits filled the interior part of the basin and have been subsequently eroded (?post-Miocene). Remote sensing data could clarify, corroborate or refute these speculations.

We have not applied remote sensing data to our studies in the northeastern Wind River Basin. However, we recognize the importance and advantage of using and applying this data to the fossil record and geologic problems as follows: 1) Evolutionary studies require detailed stratigraphic and structural data on an exposure to exposure scale to insure accurate and precise correlation of individual fossiliferous horizons. Remote sensing data would be useful in detailing the stratigraphy of isolated exposures as well as determining the presence of structural features that could effect correlation; 2) Fossil concentrations and the sedimentology and mineralogy of a horizon appear to be highly correlated. In the preliminary stages of exploration, remote sensing data could be used to identify those areas with high probabilities for the occurrence of fossils. It could also aid in reconstructing the depositional environment of highly fossiliferous areas (for example, identifying linear sandstone bodies within the Wind River Formation); and 3) Remote sensing data could substantiate the identification of the Indian Meadows and Wagon Bed formations in the Badwater Creek area. The type areas for these formations lie, respectively in the northeastern and southwestern parts of the Wind River Basin.

On the other hand, detailed biostratigraphic and lithostratigraphic studies can aid in testing the precision and accuracy of observations resulting from Remote Sensing Data.

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APPENDIX C

BASIN RESEARCH QUESTIONNAIRE

(1) Name & Affiliation:

(2) Area of Interest/Expertise:

(3) How Do You Define "Basin Analysis"?

(4) What do you think are the most important research problems that need to be studied in investigating sedimentary basins? Any specific problems associated with foreland basins or the Wind River/Bighorn Basin area of Wyoming? Any specific locations in the Wind River/Bighorn Basin area for studying these problems?

(5) What geological data and methods of analysis provide information that can be used to study problems noted in (4)?

(6) Remote sensing data can provide surface geological information. What types of surface geological information (and at what scales) could contribute to solving problems identified in (4)? How could such surface information be used in conjunction with data identified in (5)?

APPENDIX D

TOPICAL DISCUSSION REPORTS

REPORT OF PRE-LARAMIDE STRATIGRAPHY GROUP
BY
R.W. MARRS

Chair: Marrs
Participants: Bailey, Burbank, Dudley, Evans, Hallam, Huffman, Johnson, Lang, Leith, Peterson, Schenck, Singer

This group decided to approach the discussion by identifying first the data elements that would be of significance in defining important aspects of Pre-Laramide stratigraphy as it applies to "basin analysis." We attempted to define "basin analysis" but determined that the term was ambiguous and its meaning dependent on the interests and background of the individual researcher. Economic geologists, stratigraphers, geomorphologists, and structural geologists all have somewhat different concepts of "basin analysis". The approach used in the Wind River/Bighorn Basin project should address the needs of these disciplines.

The Pre-Laramide Stratigraphy Group intentionally avoided narrowing discussions to particular problems and sites. The application of remote sensing to basin analysis should remain as nearly basin-wide as possible. We must not lose sight of the advantages provided by satellite data in viewing basin-wide changes and interrelationships. If possible, this aspect should not be compromised by focusing on small sites and specific problems. Such focusing may be necessary to develop techniques or to establish patterns that can be used to construct models; but we must look at the entire basin and its surroundings if possible.

It was agreed that the primary goal of Pre-Laramide studies in the Wind River/Bighorn Basin area should be to determine a correct stratigraphic sequence and identify the major lithologic units. Remote sensing data are applicable to this goal. Detailed information is desirable in several areas, including 1) facies identification and correlation, 2) relationships between structural features and patterns of sedimentation, 3) geochronology, and 4) evaluation of basin models. The following outline summarizes the important aspects of each of these topics as discussed. The application of remote sensing methods in some of these areas is well demonstrated, in others it is questionable or unlikely; but its application in each area should be considered carefully to maximize the potential of remote sensing for studying sedimentary basins.

A. FACIES IDENTIFICATION AND CORRELATION AS RELATED TO INTERPRETING DEPOSITIONAL ENVIRONMENTS

(1) Lithologic Facies

(a) Geometry

(b) Grain size

(c) Mineralogy

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(d) Sedimentary structures

(e) Porosity

(f) Sequence analysis, including fining-up and cyclicity

(2) Chemical Facies and Contrasts

(a) Primary (as above)

(b) Diagenetic and hydrologic contrasts

1 Carbonate species

2 Organic content

3 Clay mineralogy

4 Fe species

5 Zeolites

6 Thermal maturity

(c) Zones of mineralization and hydrothermal alteration

(d) Spectral facies

1 Vegetation

2 Illumination

3 Moisture

4 Surface roughness

5 Color

6 Broad and narrow band image, field and laboratory spectrometry

B. RELATIONSHIP BETWEEN STRUCTURAL FEATURES AND PATTERNS OF SEDIMENTATION

(1) Lithology (as above)

(a) Overall chemistry and mineralogy

(b) Facies gradations

(2) Geometry of Lithologic Units

(a) Thickness

(b) Distribution

(c) Paleocurrent directions

(d) Paleogeomorphology

(e) Spatial relationships between lithologic units and structures (faults, folds, fracture patterns, lineaments, and tilting and subsidence history)

(3) Unconformities

(a) Nature

(b) Distribution

(c) Boundary lithologic units

C. GEOCHRONOLOGY

(1) Time Lines

(a) Isochronous

1 Ash beds

2 Cosmic events

3 Floods

(b) Event markers (gradational)

1 Specific lithologies

2 Anoxic sediments

3 Unconformities

(2) Biostratigraphy, Radiostratigraphy and Magnetostratigraphy (Sampling Site Selection)

(a) Fossil-bearing strata

1 Marine sequences

2 Carbonates

3 Calcareous, clay-bearing strata

4 Dark organic shales

5 Glauconitic beds

(b) Radiometrically datable units

<u>1</u> Tuffs and tuffaceous claystones

<u>2</u> Celadonite

<u>3</u> Glauconite

<u>4</u> Layered intrusive and extrusive igneous rocks

(c) Rocks susceptible to paleomagnetic measurements

<u>1</u> Fine-grained, unoxidized strata

<u>2</u> Thick and continuous exposures of strata

D. DEVELOPMENT AND EVALUATION OF BASIN MODELS

(1) Develop New Models Based on Remote Sensing Interpretations and Published Data

(2) Modify Previous Models

(3) Test Aspe -f Each Model

(4) Revise Modt

REPORT OF POST-LARAMIDE STRATIGRAPHY GROUP
BY
S. AGARD

Chair: Agard
Participants: Conel, Krishtalka, Stucky

The group defined basin analysis as "the study of the stratigraphic (depositional and erosional events), structural/tectonic, and biological history of a sedimentary basin."

GENERAL RESEARCH QUESTIONS

The Post-Laramide stratigraphic record of the Wind River/Bighorn Basin area can be subdivided into two major intervals that reflect 1) Pre-Pliocene basin aggradation and 2) Pliocene/Quaternary degradation. Post-Laramide stratigraphy of the area differs from that of the Pre-Laramide by 1) a greater heterogeneity of lithologies/facies over relatively short distances and 2) the more direct influence of basin tectonics on the Post-Laramide record.

Some general research topics involving Paleogene stratigraphy are:

(1) Identifying and mapping the distribution of deposits

(2) Identifying facies and interpreting environments of deposition

(3) Correlation of stratigraphic units and facies

(4) Determining the structural/tectonic framework controlling deposition and identifying structural/tectonic changes through time.

Some general research topics involving Neogene stratigraphy are:

(1) Identifying and mapping the distribution of deposits and landforms

(2) Establishing a relative and absolute chronology of depositional and erosional events

(3) Correlating deposits and events within and between basins

(4) Determining geomorphic, tectonic and climatic controls on landform development

Specific research problems identified in the Wind River Basin are:

(1) Can widespread and widely separated outcrops previously mapped as Middle to Late Eocene Wagon Bed Formation be correlated within the basin? Are local or basinwide sources for these deposits predominant? The same questions apply to Paleogene deposits, and relate to the extent and timing of basin filling during Post-Laramide time.

(2) Was the Wind River Basin filled during the Tertiary? When? How often? To what level?

(3) Members of the Wind River Formation have not been mapped and correlated throughout the basin. Can members defined at specific type localities be identified and mapped in other parts of the basin? What is the distribution and relationship of depositional facies of the Wind River Formation throughout the basin? What are the tectonic controls? What are the biostratigraphic relations within the formation?

(4) Can outcrops of the Indian Meadows Formation on the northwest face of Cedar Ridge in the eastern part of the basin be correlated with the type section in the northwest corner of the basin?

(5) Are relict "Eocene" fan landforms present in the Wind River Basin?

(6) What is the nature of the contact between the Lysite and Lost Cabin Members of the Wind River Formation?

(7) To what extent can lithofacies (e.g., sandstone channel fill, overbank deposits, redbeds) be mapped within the Wind River Formation?

(8) What is the distribution of Quaternary terrace deposits? What is the correlation of terraces across the Wind River? Using ashes, soil stratigraphy, terrace levels, etc., can the relative and absolute chronology of terrace formation be determined?

(9) What is the relative chronology of alluvial fan formation on the northern margin of the basin and terrace formation to the south?

(10) What are the incision rates for the basin and surrounding uplifts?

(11) What controls the present drainage pattern? Is there evidence of Eocene stratigraphic or structural control on this pattern? What lithologic, tectonic, or climatic influences affected this pattern? What factors influence the apparent present-day geomorphic differences east and west of Wind River?

(12) What major linear features exist and what do they mean?

Data and methods to be used to address these research problems include:

(1) Photogeologic interpretation

(2) Topographic analysis

(3) Soil and vegetation analysis

(4) Borehole data

(5) Field and laboratory studies to support stratigraphic investigations. These include spectral reflectance measurements, biostratigraphy and paleontology, paleomagnetic analysis and radiometric dating.

Some important applications of remote sensing methods include:

(1) Appropriate images can provide a) a geometrically accurate cartographic base and b) a synoptic overview of structural, lithologic, and geomorphic patterns.

(2) Spectral reflectance properties may allow a) correlation of Paleogene and Neogene units, b) correlation and relative dating of Quaternary units and c) discrimination of lithofacies.

Because of the complexity and heterogeneity of Post-Laramide stratigraphy, some remote sensing methods may be more applicable in a restricted geographic area rather than over large regions. Most problems posed above will be answered by detailed fieldwork and analysis of large scale aerial photographs, but remote sensing may aid in identifying critical areas for these detailed studies.

REPORT OF STRUCTURE/TECTONICS GROUP
BY
E. PAYLOR

Chair: Berger
Participants: Anderson, Blackstone, Blom, Burbank, Green, Gubbels, Keefer, Kulik, Leith, McGuffie, Paylor, Sawatzky

The Structure/Tectonics Group agreed that typical structures of the Wyoming Foreland are asymmetric folds with reverse faulting of steeper dipping limbs. Structural relief of tens of thousands of feet is characteristic of the region. Basement structural involvement is common. Recent deep drilling and seismic data confirm the existence of low angle thrusts in the region and suggest that the foreland was subjected to NE-SW compression during Laramide deformation. This resulted in significant basement shortening. The Wyoming Foreland, particularly the Wind River/Bighorn Basin area, is somewhat unique compared to the rest of the Rocky Mountain Foreland because of the existence of so-called "zones of asymmetry" (areas of apparently independent tectonic translation). These zones result in structural compartmentalism and complexity. After over a century of geologic research, major unresolved structural/tectonic problems still exist in the Wind River/Bighorn Basin area, making it a challenging region to test new remote sensing methods.

Participants agreed that remote sensing is only one of many tools which can be used for studying the structure/tectonics of sedimentary basins. Geophysical data were consistently mentioned as an important data type for conducting structural/tectonic research. Seismic data were considered to be the most valuable. It was emphasized that remote sensing results should be correlated with seismic and other geophysical data, as well as geological data, in order to confirm or enhance structural interpretation and tectonic models.

The group made several specific recommendations and suggestions for conducting remote structural/tectonic research in the Wind River/Bighorn Basin investigation. These include:

(1) Limitations of remote sensing methods for studying the structure/tectonics of sedimentary basins should be evaluated. These limitations relate in part to the type of basin, the environmental setting (e.g., arid climate) and the requirement of sedimentary/basement rock exposures on basin margins.

(2) Analysis of TM satellite data, rather than experimental aircraft data, should be emphasized because these data are most accessible to the academic, government, and industry research community.

(3) The greatest contribution of remote sensing methods will probably be in improved mapping of basin margins, including stratigraphy, facies, and structure/fracture trends. The determination of "spectral signatures" of basin filling strata is an extremely important area of remote sensing research. Mapping results should be correlated with geophysical data and projected to depth. This information will contribute to unraveling the sequence and the timing of tectonic events.

(4) Photogeologic and spectral methods for identifying and mapping "hidden" structures, particularly buried or concealed faults, should be developed.

(5) Three specific structural mapping exercises were suggested:

(a) Map basement; determine regional fracture (lineament) trends, project trends across basins and into other areas of basement exposure and correlate with geologic and geophysical data. This information will help determine the nature of basement involvement in Laramide deformation: Does basement fold or flex under stress or does it react rigidly (shear with micro-fractures) during deformation?

(b) Map Post-Laramide strata; particularly in basin interior. Examine facies and fracture patterns in a search for surface expression of underlying structure.

(c) Map the Absaroka Volcanics. Examine facies, mineralogy and fracture patterns in a search for surface expression of underlying structure.

(6) Methods developed in the Wind River/Bighorn Basin study should be applied/tested in "frontier areas" (those less well mapped, drilled, and surveyed geophysically).

(7) Involvement of other government, academic and industry researchers should be maintained throughout the study. Such involvement provides a source of data and of advice. Periodic, formal or informal project reviews or workshops might be beneficial.

REPORT OF DATA INTEGRATION GROUP
BY
T. LOGAN

Chair: Logan
Participants: Adams, Evans, Blake, Bruckenthal, Guinness, Knepper, McKeon, Schmoker, Sultan

The integration of geologic data for the analysis of sedimentary basins can be approached from two perspectives: (1) identification of general geologic data types and their usage, or (2) definition of specific data processing techniques. The Data Integration Group chose to identify the general types of geologic data that should be considered in the analysis of sedimentary basins because specific processing techniques require the a priori definition of specific sedimentary basin analysis problems. Identification of these problems was the subject of three other discussion groups in concurrent session with this discussion group, and were therefore not available in advance.

The geologic data types that could potentially be used for sedimentary basin analysis can be divided into "surface," "subsurface," and "evolutionary" categories. The data in each of these categories can be further subdivided by their format into "areal" data, "line/profile" data, and "point" data, and these in turn can be considered in terms of "regional" scale, "basin" scale, and "local" scale. The data identified for potential use in the analysis of sedimentary basins via the above categorization is provided in Table D-1. Additionally, the level of need for each data type to be placed in digital image co-registration is identified using a four-level rating system (M=Must/Required; R=Recommended; O=Optional; X=Don't).

An important issue raised by the committee pertains to the relative role that non-remote sensing data should play in the analysis of sedimentary basins. It can be argued that remote sensing is just one of many tools that can be used in the analysis. It can also be argued that one of the purposes of this research is to emphasize the remote sensing tool in order to evaluate its potential. The group recommends that remote sensing datasets be given the highest priority, but that non-remote sensing datasets be considered as necessary, in a stepwise manner, until at least a level of analysis commensurate with conventional techniques and data types is obtained. This research has the maneuverability of equally evaluating the utility of all data types without undue bias. It was observed that many organizations do not normally have the similar flexibility of exploring, or equally evaluating, new data types because of historic or profit-oriented biases.

Several problems associated with integrating various data types were identified. Serious errors can occur when data generated at different scales, from different sources, and at different levels of accuracy are combined. Careful consideration of each data type is therefore important if meaningful analysis is to be obtained.

The Data Integration Group strongly recommends that the analysis of available data be conducted from a deductive rather than an inductive perspective.

Table D-1. Potentially Useful Geologic Data by Type and Format

Type	Format					
	Areal	Line/ Profile	Point	Regional/ Basin Scale	Local Scale	Co- Register*
SURFACE						
Base Maps	X			X	X	O
Geologic Maps	X			X	X	M
Lithofacies Maps	X			X	X	M
Biofacies Maps	X			X	X	M
Fault Maps		X		X	?	M
Air Photographs	X			?	X	X
TM	X			X	X	M
MSS	X			X	X	M
TIMS/TMS	X				X	M
AIS	X				X	R
Radar	X			X	X	R
Digital Terrain	X			X	X	M
Field Observations	X	X	X	X	X	X
Measured Sections		X			X	X
Chemistry/Petrography			X		X	X
Field/Lab Spectra			X		X	X
Rock Elemental Analysis			X		X	X
SUBSURFACE AND GEOPHYSICAL						
Oil & Gas Maps	X			X	X	O
Magnetic Data	X			X	X	M
Gravity Data	X			X	X	M
Profile Data Location	X				X	O
Isopach	X			X		R
Well Log		X			X	O
Core/Cutting Description		X			X	O
Seismic		X		X	X	R
EVOLUTIONARY						
Crustal				X		O
Geochemical	X			X		O

*M Must/Required
R Recommended
O Optional
X Don't

Data should not just be combined and processed because it is available; rather, specific sedimentary basin problems should be identified, and the appropriate data types and methodologies suitable for solving those problems should be selected with deference to the implications of processing and applying those data. A general flowchart for data integration was prepared for use as a guide (Figure D-1).

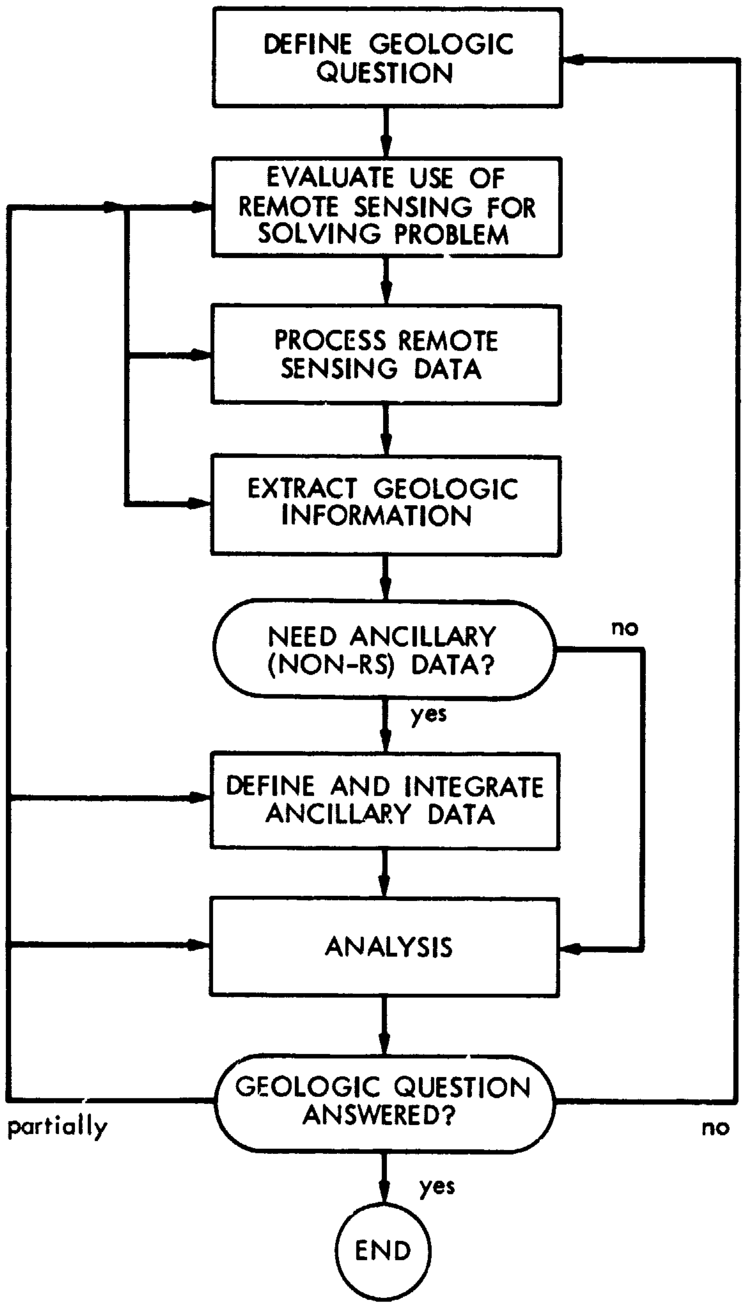

Figure D-1. General flowchart for integrating sedimentary basins data

APPENDIX E

AGENDA

TIME	TOPIC	PRESENTER
THURSDAY, JANUARY 10, 1985		
8:15 a.m.	GENERAL SESSION	
	Introduction	Fouch, Kitcho, Lang
8:45 a.m.	Geologic Overview of North American Western Interior With Reference to Wyoming Foreland Basins and Wind River/Bighorn Basin Area	Love
9:30 a.m.	Structural/Tectonic Overview of Wind River/ Bighorn Basin Area	Blackstone
10:35 a.m.	Stratigraphic Overview of the Wind River/ Bighorn Basin Area	Keefer
11:15 a.m.	BREAK	
11:30 a.m.	An Exploration Industry View of Basin Analysis and the Utility of Remote Sensing	Berger
12:00 noon	Stratigraphic and Structural Analysis Capabilities of New Remote Sensing Data: Wind River/Bighorn Basin Examples	Lang
12:30 p.m.	Review and Plan Topical Discussion Groups	Lang
12:45 p.m.	BREAK FOR LUNCH	
1:30 p.m.	RECONVENE IN DISCUSSION GROUPS	All Participants
	Pre-Laramide Stratigraphy Post-Laramide Stratigraphy Structure/Tectonics Data Integration	
5:00 p.m.	ADJOURN	
FRIDAY, JANUARY 11, 1985		
8:30 a.m.	RECONVENE IN DISCUSSION GROUPS	All Participants
1:00 p.m.	RECONVENE GENERAL SESSION	
	Stratigraphic Evidence for Pre-Laramide Structural Control of Wyoming Foreland Evolution	Peterson
2:15 p.m.	Reports and Discussions of Topical Discussion Results:	
	Pre-Laramide Stratigraphy	Marrs
	Post-Laramide Stratigraphy	Agard
	Structure/Tectonics	Berger
	Data Integration	Logan
5:00 p.m.	ADJOURN	

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