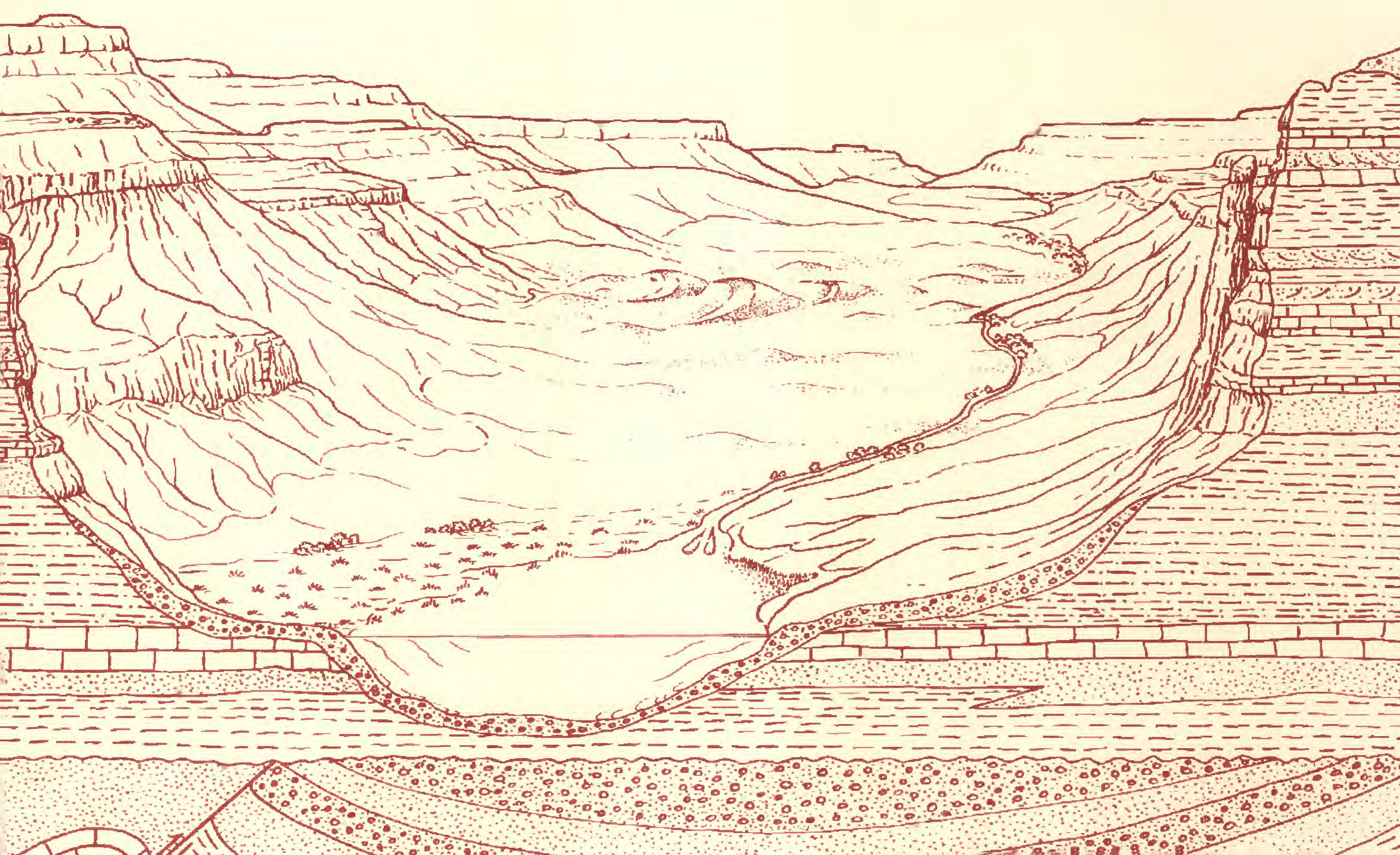
Structural Control on Distribution of Sedimentary Facies in the Pennsylvanian Minturn Formation of North-Central Colorado

U.S. GEOLOGICAL SURVEY BULLETIN 1787–Y



AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that are listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" are no longer available.

Prices of reports released to the open files are given in the listing "U.S. Geological Survey Open-File Reports," updated monthly, which is for sale in microfiche from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of periodicals (Earthquakes & Volcanoes, Preliminary Determination of Epicenters), and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Books and Open-File Reports Section
Federal Center, Box 25425
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from

Superintendent of Documents
U.S. Government Printing Office
Washington, DC 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Federal Center, Box 25286
Denver, CO 80225

Residents of Alaska may order maps from

U.S. Geological Survey, Map Distribution
New Federal Building - Box 12
101 Twelfth Ave., Fairbanks, AK 99701

OVER THE COUNTER

Books

Books of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey offices, all of which are authorized agents of the Superintendent of Documents:

- **ANCHORAGE, Alaska**—4230 University Dr., Rm. 101
- **ANCHORAGE, Alaska**—605 West 4th Ave., Rm. G–84
- **DENVER, Colorado**—Federal Bldg., Rm. 169, 1961 Stout St.
- **LOS ANGELES, California**—Federal Bldg., Rm. 7638, 300 North Los Angeles St.
- **MENLO PARK, California**—Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**—National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**—Federal Bldg., Rm. 8105, 125 South State St.
- **SAN FRANCISCO, California**—Customhouse, Rm. 504, 555 Battery St.
- **SPOKANE, Washington**—U.S. Courthouse, Rm. 678, West 920 Riverside Ave.
- **WASHINGTON, DC**—U.S. Department of the Interior Bldg., Rm. 2650, 1849 C St., NW.

Maps

Maps may be purchased over the counter at the U.S. Geological Survey offices where books are sold (all addresses in above list) and at the following U.S. Geological Survey offices:

- **ROLLA, Missouri**—1400 Independence Rd.
- **FAIRBANKS, Alaska**—New Federal Bldg., 101 Twelfth Ave.

Chapter Y

Structural Control on Distribution of Sedimentary Facies in the Pennsylvanian Minturn Formation of North-Central Colorado

By KAREN J. HOUCK

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1787

EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1991

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center
Box 25425
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Houck, Karen J.
Structural control on distribution of sedimentary facies in the Pennsylvanian Minturn Formation of north-central Colorado / by Karen J. Houck.
p. cm. — (Evolution of sedimentary basins—Uinta and Piceance basins; ch. Y) (U.S. Geological Survey bulletin ; 1787–Y)
"A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern."
Includes bibliographical references.
Supt. of Docs. no.: I 19.3: 1787Y
1. Sedimentation and deposition—Colorado—Eagle County. 2. Geology, Stratigraphic—Pennsylvanian. 3. Geology, Structural—Colorado—Eagle County. 4. Minturn Formation (Colo.) I. Title. II. Series. III. Series: U.S. Geological Survey bulletin ; 1787–Y.
QE75.B9 no. 1787–Y
[QE571]
557.3 s—dc20 91–22419
[552'.5'0978844] CIP

CONTENTS

FIGURES

Structural Control on Distribution of Sedimentary Facies in the Pennsylvanian Minturn Formation of North-Central Colorado

By Karen J. Houck[1]

Abstract

Field study of the middle part of the Pennsylvanian Minturn Formation in the McCoy-Bond area of north-central Colorado has yielded evidence for structural influences on sedimentation. The McCoy-Bond area was probably located near an en echelon offset in the fault zone bounding the eastern margin of the basin. Paleocurrent measurements show that sediment transport in nonmarine drainages and in marine deltas and turbidites was consistently to the south during several transgressive-regressive intervals. These trends may have been controlled by a topographic low that extended south from the offset zone to a termination in the southern part of the area. Mapping of sediment packages shows that drainages and sites of delta and turbidite accumulation were repeatedly established near the traces of two north-south-oriented faults. The sediment packages also thicken and are more completely preserved closer to the fault traces. These trends suggest that these faults were active during middle Minturn deposition.

Individual fault blocks delineated by facies and thickness changes are similar in structural style to the Vail-McCoy trough, the Avon-Edwards high, and the Eagle sub-basin defined by other workers and illustrate the control of structure on sedimentation in the central Colorado basin.

INTRODUCTION

The purpose of this paper is to document paleocurrent trends and facies distributions in depositional sequences in the Pennsylvanian Minturn Formation near the villages of McCoy and Bond, Colorado. A secondary purpose is to provide a possible explanation that relates these trends and distributions to fault movements that occurred along the basin margin.

The Minturn Formation is a thick (as much as 1,921 m, 6,300 ft) accumulation of clastic and minor carbonate sediments deposited along the eastern margin of the central Colorado basin during Middle Pennsylvanian (Atokan and Desmoinesian) time (Chronic and Stevens, 1958; DeVoto, 1972; Tweto and Lovering, 1977). The source of the arkosic clastic sediments probably was the Ancestral Front Range, which flanked the basin on its east side (Mallory, 1972; DeVoto, 1980) (fig. 1). Stevens (1958) showed that the Minturn Formation is approximately 610 m (2,000 ft) thick in the McCoy area. He divided the Minturn into 19 stratigraphic units that are traceable throughout the McCoy-Bond area (Chronic and Stevens, 1958; Stevens, 1958). I have continued to use his numbering scheme in my work, which encompasses about 240 m (800 ft) of section from the base of Stevens' unit 3 to the top of his unit 6 (fig. 2).

Numerous relative sea-level changes during deposition of the Minturn Formation resulted in a series of transgressive-regressive sedimentary cycles (Houck and Lockley, 1986). These cycles average about 30 m (100 ft) in thickness and contain a variety of marine and nonmarine deposits. The cycles are traceable through two paleodrainages and the intervening divide and are thus presumed to be allocyclic in nature (Beerbower, 1964).

Two unexpected discoveries were made in the course of mapping lateral facies variations and taking paleocurrent measurements in these cycles. First, though the study area is on the eastern margin of the basin, Minturn fluvial systems repeatedly flowed to the south, rather than to the west. Second, stream drainages, deltas, and turbidites were

Manuscript approved for publication May 21, 1991.

[1]Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309–0250.

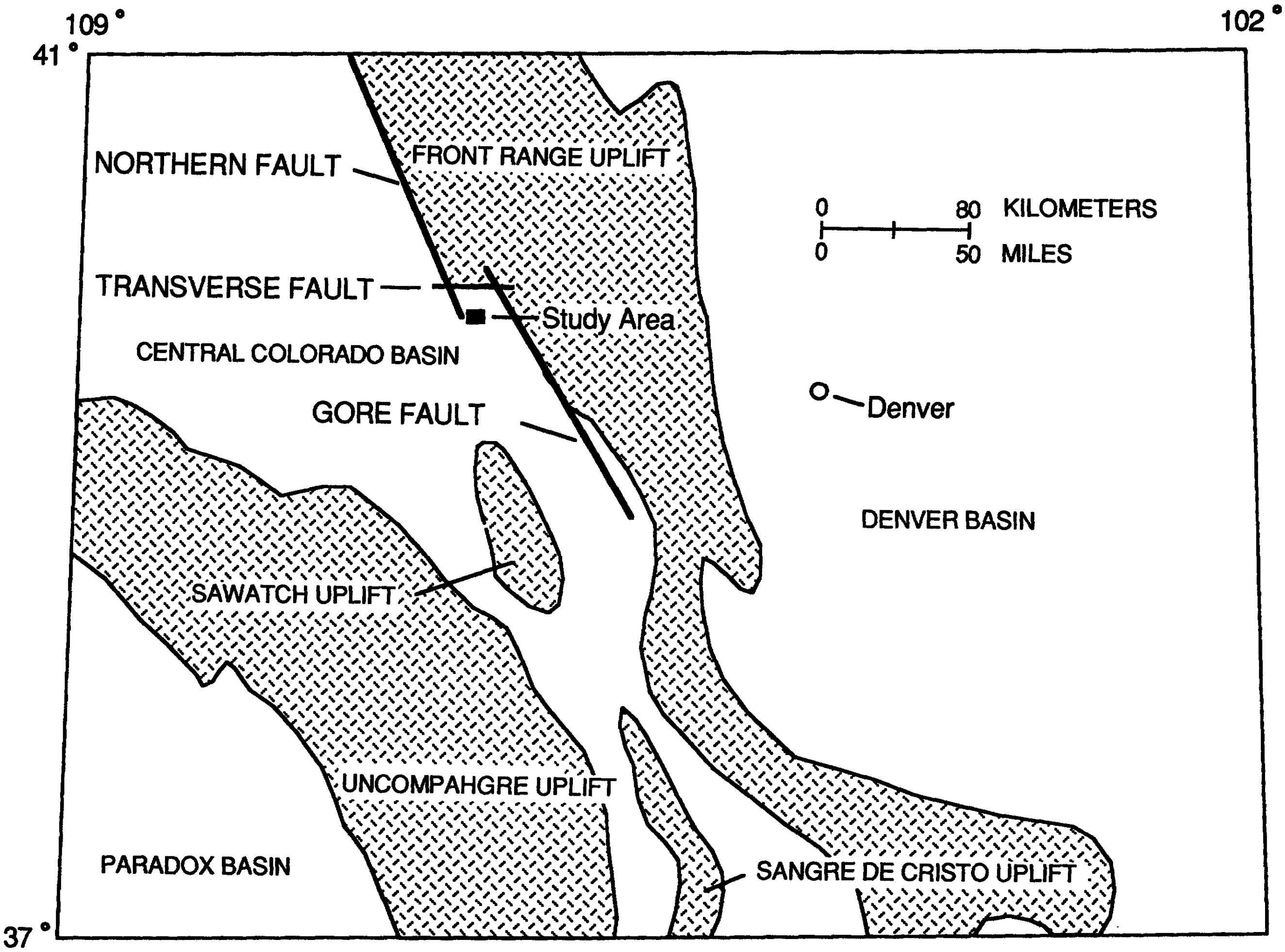


Figure 1. Generalized paleogeographic map of Colorado showing location of the study area on the eastern margin of the Central Colorado basin and approximate locations of the Gore, transverse, and northern fault zones. Pattern delineates uplifted areas. Modified from DeVoto (1980) and DeVoto and others (1986).

repeatedly established in geographically restricted parts of the area and are thus "stacked" in vertical sections through the study interval. I interpret these paleocurrent trends and facies patterns to be the sedimentary response to fault movement and differential subsidence along the tectonically active margin of the central Colorado basin.

Acknowledgments.—I thank the residents of Bond, McCoy, and Copper Spur for providing me with access to their property. Without their cooperation, this study would not have been possible. I also thank the Rocky Mountain Section of the Society for Sedimentary Geology (SEPM), the Colorado Mountain Club, Union Pacific Resources, and the Department of Geological Sciences at University of Colorado for financial support through three field seasons. An early version of the manuscript was reviewed by Bill Bilodeau and Ted Walker (University of Colorado). The version submitted for publication was reviewed by Sam Johnson and Chris Schenk (U.S. Geological Survey). Their comments resulted in a substantial improvement. I thank Al Scott for drawing the block diagram (fig. 16) and Rick Allmendinger for use of his Stereonet 3.6 program.

STRUCTURAL SETTING

During Pennsylvanian time, the central Colorado basin was an elongate, narrow, northwest-southeast-oriented feature. The Pennsylvanian basin fill is as thick as 3,050 m (10,000 ft) (Mallory, 1972; DeVoto, 1980). Fault zones are thought to have formed the eastern margin of the basin. These faults were active during Laramide (early Tertiary) deformation but are inferred to have had an earlier Pennsylvanian history as well (DeVoto, 1980; Tweto, 1980; DeVoto and others, 1986). The Gore fault zone, 19 km (12 mi) east of the McCoy-Bond area, was active during Pennsylvanian time (Tweto, 1977; Tweto and Lovering, 1977). The Gore fault and related structures have undergone a large amount of dip-slip movement; DeVoto and

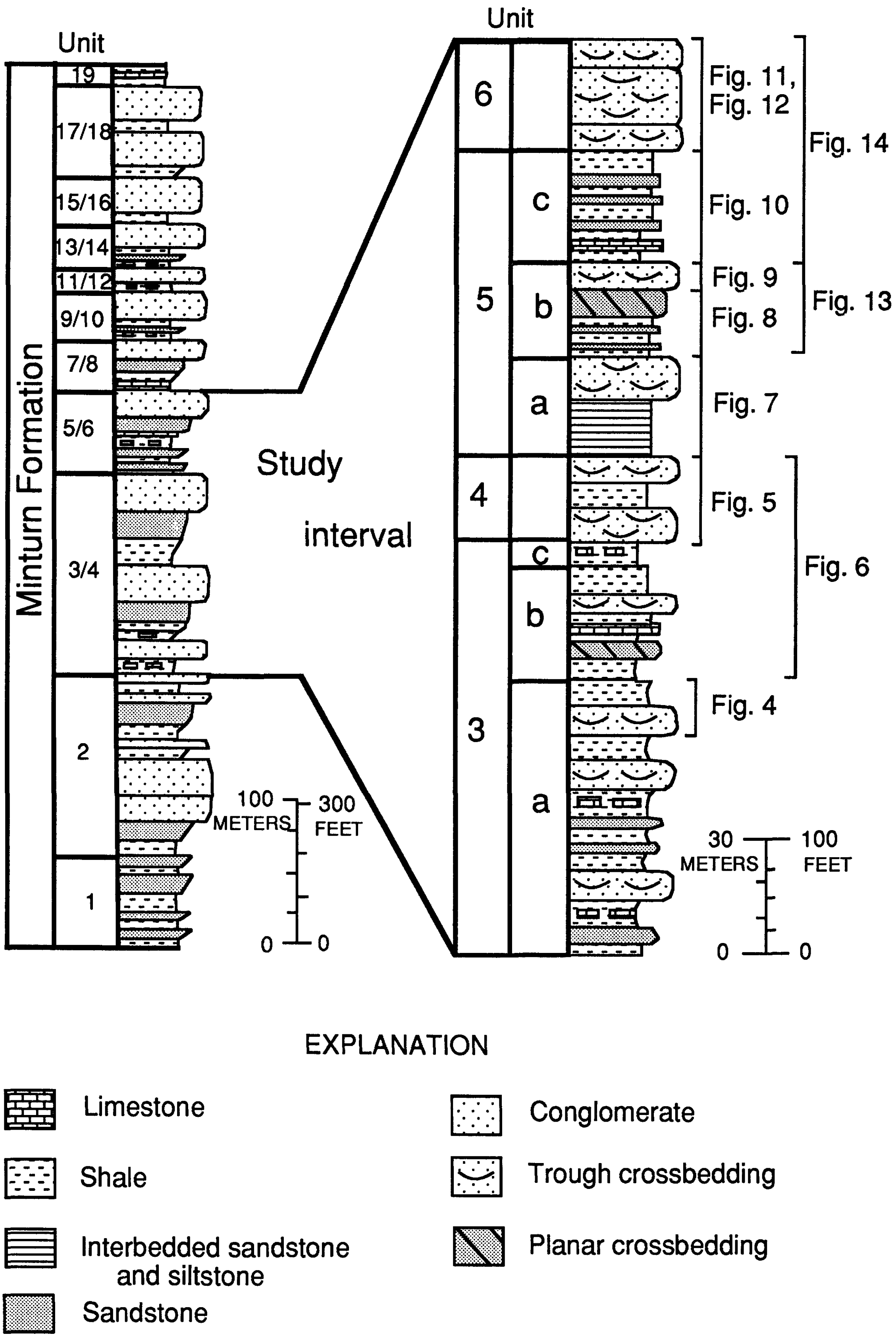


Figure 2. Stratigraphy of the Pennsylvanian Minturn Formation in the study area near McCoy, Colorado. The interval described in this report is enlarged at right. Stratigraphic positions of units depicted in figures 4–14 are shown along the right margin. Numbering system of units is from Chronic and Stevens (1958).

others (1986) estimated that 1,525–2,135 m (5,000–7,000 ft) of offset occurred during the Desmoinesian alone. The amount of Pennsylvanian strike-slip movement on these faults (if any) is not known (Kluth, 1986). Faults within the Gore zone display a variety of orientations, but most are almost vertical and the zone as a whole is considered to be vertical (Tweto and Lovering, 1977).

The bounding fault zones along the eastern margin of the basin presently have an en echelon configuration, and it is presumed that this was also the situation during the Pennsylvanian (DeVoto, 1980). The McCoy-Bond area is west of one of these areas of en echelon offset. The northern end of the Gore fault zone is truncated there by an east-west-oriented transverse fault that offsets the basin margin 16 km (10 mi) to the west. North of this transverse fault, an unnamed north-trending fault zone forms the basin margin (Tweto, 1976; Tweto and others, 1978) (fig. 1). The transverse fault and unnamed northern fault zone were inferred to be active during Pennsylvanian time by DeVoto and others (1986), but, because the Minturn Formation is not present in that area, Pennsylvanian movement on these faults cannot be conclusively demonstrated.

Despite a growing understanding of its structure, the mechanism by which the central Colorado basin formed is not well understood. Kluth (1986) has shown that formation of many of the Pennsylvanian sedimentary basins in the Western Interior of the United States coincides with the progressive suturing of South America to North America along the Ouachita-Marathon orogenic front. Studies of the modern collisional zone located between India and Asia (Molnar and Tapponier, 1975) show that structural deformation can take place as much as 3,000 km (1,860 mi) into the interior of a colliding continent. This deformation is expressed in a variety of structures formed by extensional, compressional, and strike-slip movements. The central Colorado basin could theoretically have formed under any one or a combination of these stress regimes.

PROCEDURES

The Minturn Formation in the McCoy-Bond area was deformed into a series of north-south-oriented folds, and outcrops of the study interval are in belts along the fold limbs. Exposures in the outcrop belts are continuous, and beds can be traced along the surface parallel with the fold axes (fig. 3).

Thirty-three detailed sections were measured using a Jacob's staff and Brunton compass. Ten sections span the entire study interval, from the base of unit 3 to the top of unit 6 (fig. 2); the others are partial sections. Wherever possible, beds were walked out between sections. Through areas where continuous exposure was not available, correlation was made by matching strata as well as possible on the basis of lithological, faunal, and directional features (Boggs, 1987). I am reasonably confident of the correlations because the longest distance between outcrop belts in the entire study area is only 3.1 km (1.9 mi). The correlated sections served as a basis for subdividing the study section into intervals and for constructing lithofacies and paleogeographic maps of each interval.

Paleocurrent measurements were made on a variety of features including logs, tool marks, current-ripple marks, trough crossbeds, planar-tabular crossbeds, and Gilbert delta foresets. At every outcrop selected for measurement, readings were taken on as many features as were available, to a maximum of 25 for crossbeds and 50 for linear features. Data were rotated to paleohorizontal, either by hand on a stereonet or by using a computer.

PALEOCURRENT TRENDS AND SEDIMENTARY FACIES PATTERNS

The McCoy-Bond area is close to the eastern margin of the basin, so one might expect the major Pennsylvanian drainages in the area to have flowed westward, away from the scarp of the Gore fault zone. Paleocurrent data from numerous horizons situated within the 240-m (800 ft) study interval show, however, that the Minturn drainages were consistently oriented north-south through several episodes of marine transgression and regression. To illustrate this point, reconstructions of five nonmarine and three marine intervals are displayed in figures 4–13. Their positions in the study section are shown in figure 2.

Braided fluvial deposits in unit 3.—This interval is exposed as an erosionally resistant band below a laterally extensive marine limestone. Conglomerate bodies about 5–8 m (15–25 ft) thick are encased in purple siltstone. The conglomerates are granular and pebbly and have a matrix of coarse-grained sand. The most common sedimentary structures are medium-scale trough crossbedding, planar bedding, and medium-scale planar-tabular crossbedding. These conglomerate bodies are interpreted as braided fluvial deposits. Paleocurrent data from foresets in the trough and planar-tabular crossbedding indicate that flow in these braided channels was predominantly to the southeast, south, and southwest. Flow directions are dispersed radially around a north-south-oriented axis situated between Rock Creek and the Bond fault (fig. 4). Maximum clast sizes at the various locations range from about 15 cm (6 in.), presumably near major channels, to about 1 cm (½ in.), presumably away from major channels.

Braided fluvial deposits in unit 4.—In the eastern part of the study area (fig. 5) this unit is distinctive because it is unusually coarse; in the western part of the study area the unit is difficult to identify. The conglomerates are lensoid bodies of granules and pebbles in a matrix of coarse-grained sand. The conglomerate bodies have pronounced erosional relief on their lower surfaces and contain common rip-up clasts of sandstone, siltstone, and limestone. Massive

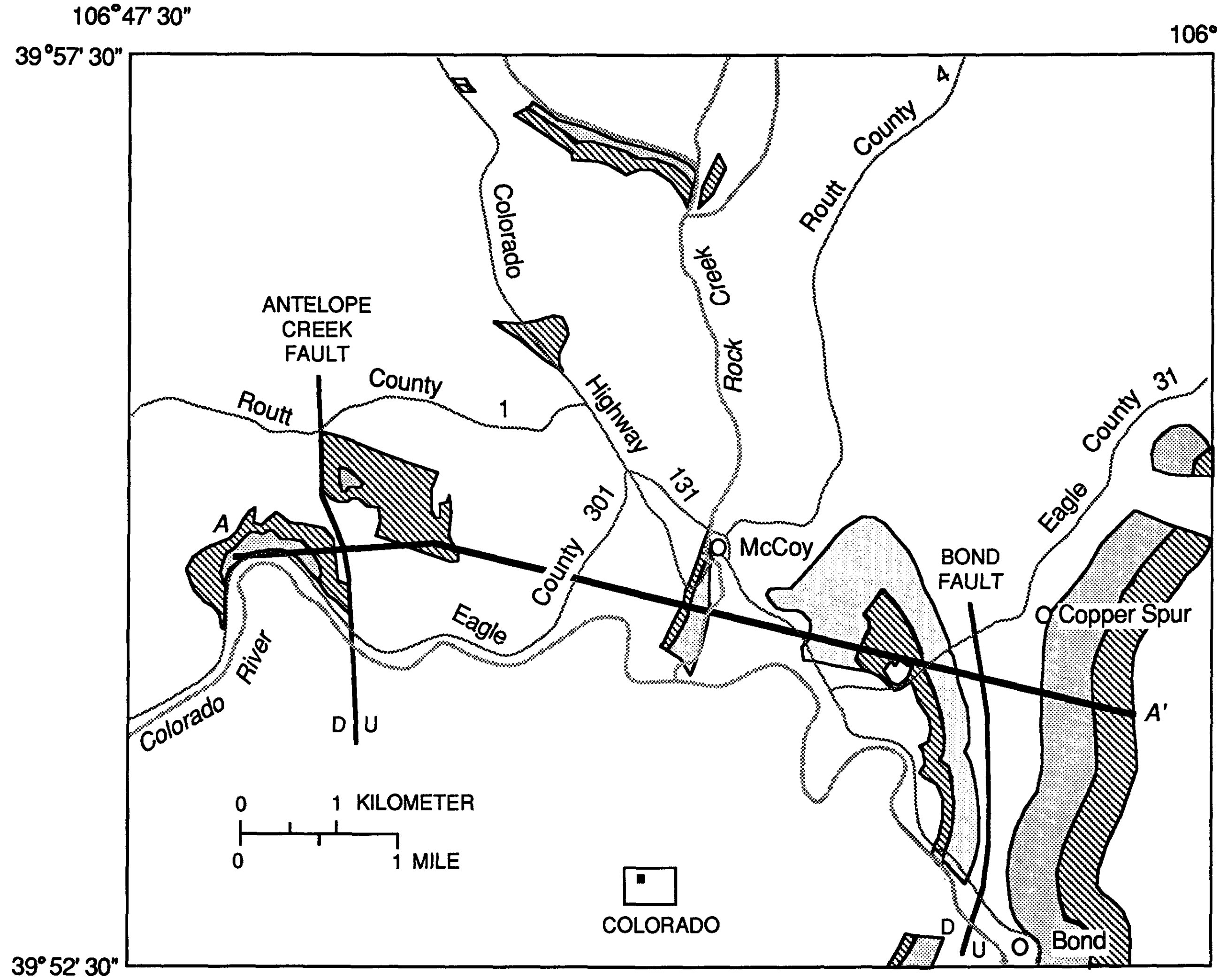


Figure 3. Outcrops of the study interval. Screen pattern indicates outcrops of units 3 and 4; diagonal pattern indicates outcrops of units 5 and 6. Locations of the Bond and Antelope Creek faults and line of cross section *A–A'* (fig. 15) are also shown.

conglomerate is along the channel bases. The conglomerate bodies are encased in purple siltstone. Trough and planar-tabular crossbedding and planar bedding are the most common structures. Current measurements taken on the trough and planar-tabular crossbedding again show a radial distribution with flow to the east, southeast, and west (fig. 5). Like the fluvial interval in unit 3, the axis of the system probably is oriented north-south and situated between Rock Creek and the Bond fault. The largest clast sizes, as much as 30 cm (12 in.) in diameter, are found north and west of Bond (fig. 5) in an area interpreted as a major channel system in the Minturn drainage network. Smaller channels are interpreted to have been present at other locations in the study area.

Erosional surface on top of unit 4.—The thickness of unit 4 is irregular in the study area. An isopach map of the interval from the base of a laterally extensive marine limestone in unit 3 to the top of unit 4 (fig. 6) shows an incised channel system that has about 40 m (130 ft) of relief. The axis of this channel system also trends roughly north and lies slightly west of Copper Spur (fig. 6). South of Eagle County Road 31, between Copper Spur and McCoy, two channels are present: one continues south through Bond, and the other trends to the southwest. This pattern of two channels, oriented southward and southwestward, continues to manifest itself in both the marine and nonmarine deposits of the next two transgressive-regressive cycles (figs. 7, 8).

Turbidity current deposits in unit 5a.—These deposits are confined to the eastern part of the study area. They consist of thinly interbedded, tan, medium-grained sandstone and dark-gray siltstone. Both the sandstone and siltstone beds are laminated on a millimeter scale. The bases of the sandstone beds contain abundant tool marks and rare flute marks. The tops commonly show primary current lineation, current ripples, and small pieces of plant debris. Paleocurrent directions based on orientations of tool marks and ripple marks show two trends, following the courses of the valleys incised into the underlying conglomerate. The

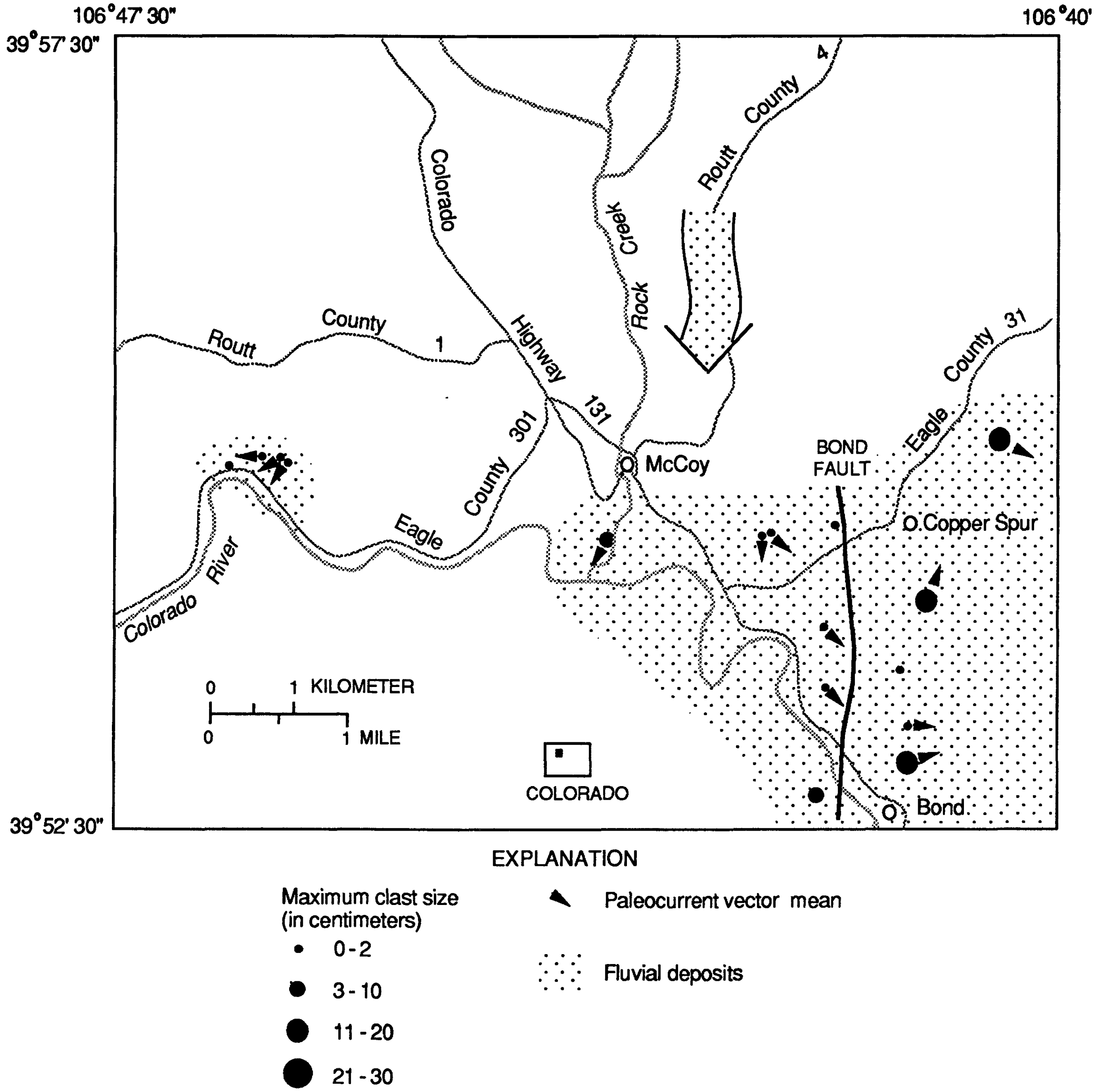


Figure 4. Paleocurrent directions and maximum clast sizes for a fluvial sequence in unit 3. Stratigraphic position of the sequence is shown in figure 2. Rose diagrams for paleocurrent vectors are given in the appendix.

deposits north and west of Bond are oriented generally to the south, whereas those west of Copper Spur are oriented to the southwest (fig. 7). South of Bond, this part of the section is made up mostly of siltstone.

Thickness variations in the turbidity current deposits are also instructive. Because the overlying fluvial deposits in unit 5a channel into the turbidites at some locations, an isopach map was made of the fluvial deposits and the turbidites together. The resulting contour map (fig. 7) shows a sediment package that fits into the valleys incised on the top of unit 4. This relationship suggests that the turbidity currents moved down the incised valleys after the valleys were drowned by a marine transgression. The turbidites and overlying fluvial deposits then filled the valleys.

Fluviodeltaic deposits in unit 5b.—This interval contains three Gilbert-type deltas (Gilbert, 1885) (fig. 8). The deltas are composed of tan, granular, coarse-grained sandstone and are encased in gray siltstone. They are characterized by large-scale planar-tangential foresets inclined at about 20°–25° and are lobate in plan view. North

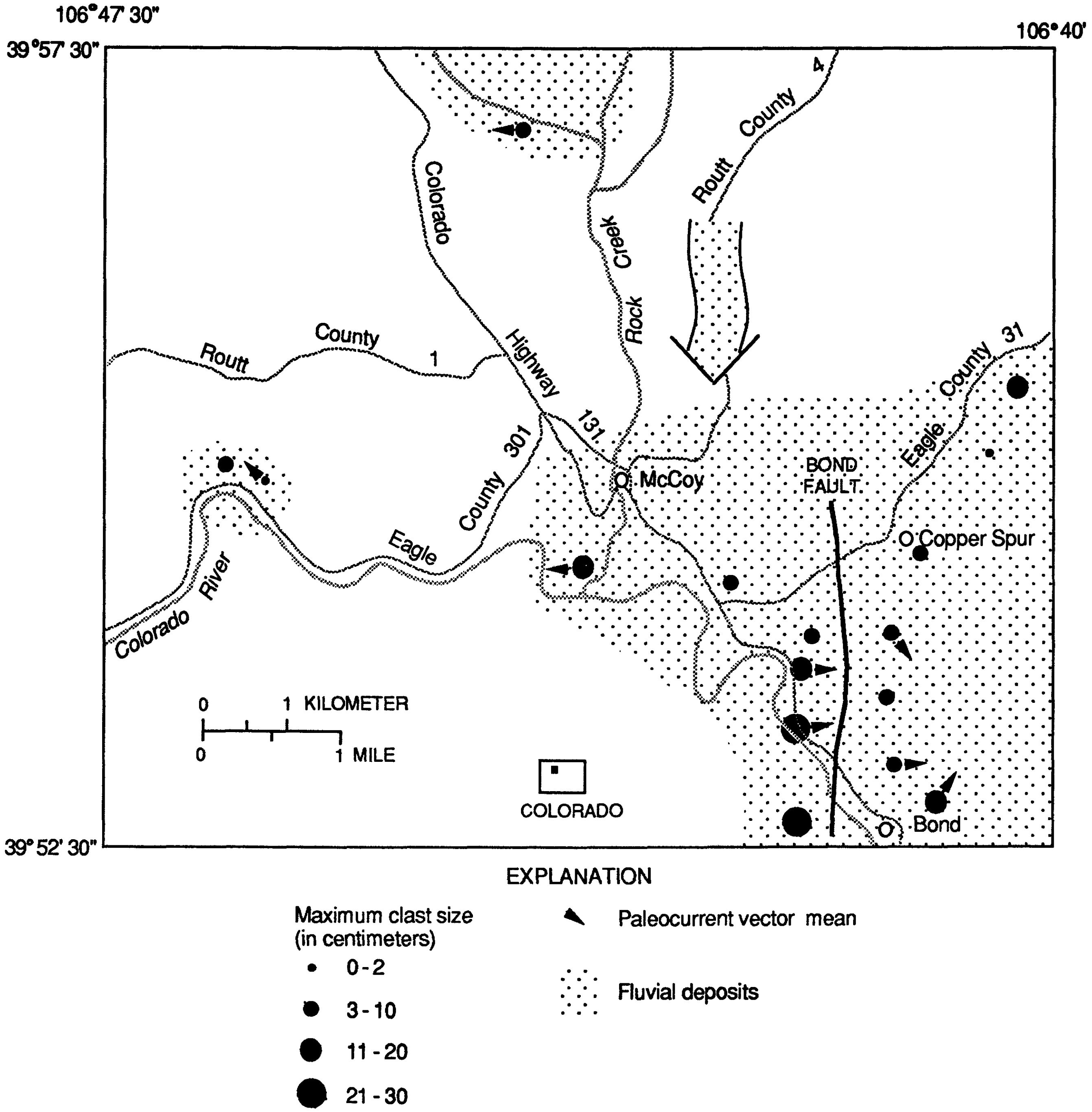


Figure 5. Paleocurrent directions and maximum clast sizes for fluvial unit 4. Stratigraphic position of the unit is shown in figure 2. Rose diagrams for paleocurrent vectors are given in the appendix.

of the Gilbert delta, outcrops are 1.5–5-m (5–15 ft)-thick bodies of tan, trough crossbedded, granular and coarse-grained sandstone containing common wood fragments. These sandstone bodies are also encased in gray siltstone. They are interpreted as fluvial deposits of the drainage systems that fed the deltas.

Paleocurrent measurements were made on the Gilbert delta foresets. Two deltas, both prograding to the south, are exposed above the south-flowing channel incised in unit 4. Another delta, prograding to the southwest, is exposed above the southwest-flowing channel. The orientation of these three deltas shows a continued trend of drainage from north to south, along channels established after deposition of unit 4.

Fluvial deposits in unit 5b.—This interval caps the aforementioned fluviodeltaic interval in unit 5b. It is composed of thick (6–12 m, 20–40 ft), laterally extensive deposits of pebbly and sandy granular conglomerate

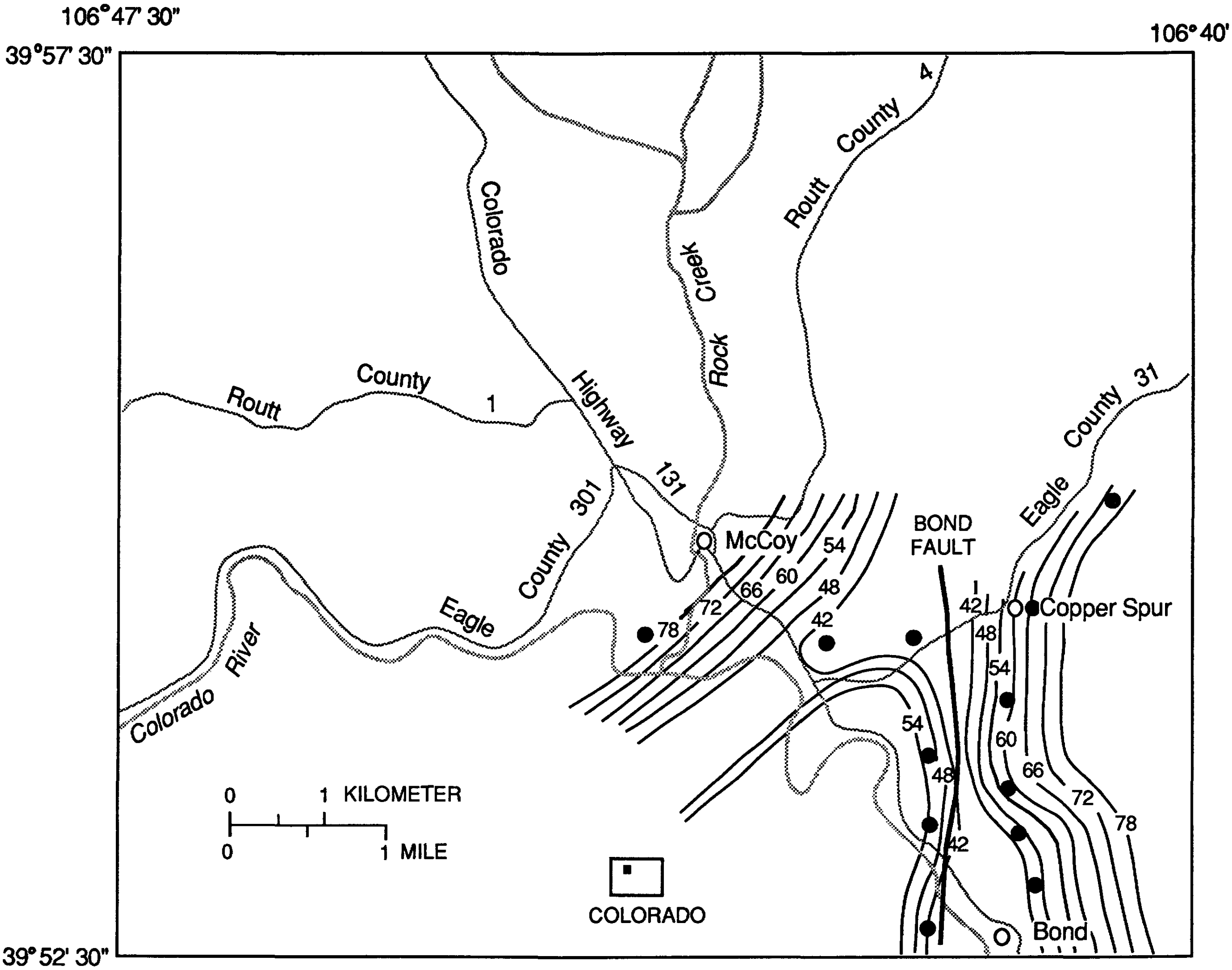


Figure 6. Isopach map showing the thickness of the interval from the base of a laterally extensive limestone in unit 3 to the top of unit 4. Stratigraphic position of the interval is shown in figure 2. Contour interval 6 m. Solid circles indicate locations of measured sections.

separated by siltstone deposits 3–6 m (10–20 ft) thick. Although cobbles as large as 25 cm (10 in.) in diameter were found at one location in the southeastern part of the study area, the maximum clast size is 15 cm (6 in.) at most locations. Trough crossbedding, planar bedding, and planar-tabular crossbedding are the most common structures. Paleocurrents were measured on the trough- and planar-tabular crossbeds. Measurements show flow to the southwest, south, and southeast (fig. 9). This flow is dispersed about the same axis as in the underlying deltaic and turbidite intervals.

Deltaic deposits in unit 5c.—Gilbert-type deltas are also present in unit 5c, but, unlike the preceding marine interval, the main sites of delta progradation are in the western part of the study area. In other respects, the deltas are similar to those of unit 5b, consisting of granular, coarse-grained sandstone in large-scale (average height 6 m, 21 ft) foresets inclined at about 20°–25°. Paleocurrent measurements show that progradation was generally toward the south and east. Strata in this interval that crop out in the area near Bond and Copper Spur contain only siltstone and thin sandstone beds (fig. 10). These sandstone and siltstone beds are inferred to be marine because they contain marine trace fossils at one location.

Braided fluvial deposits in unit 6.—Unit 6 is an unusually thick, widespread interval containing very coarse grained fluvial deposits in the western part of the study area, finer grained fluvial deposits in the central part, and Gilbert delta deposits in the southeastern part (fig. 11). The fluvial conglomerates occur as solid bands in the outcrop rather than as isolated channels in siltstone. Presumably, amalgamation of multiple channels (Allen, 1978; Leeder, 1978) produced this sheetlike appearance. The

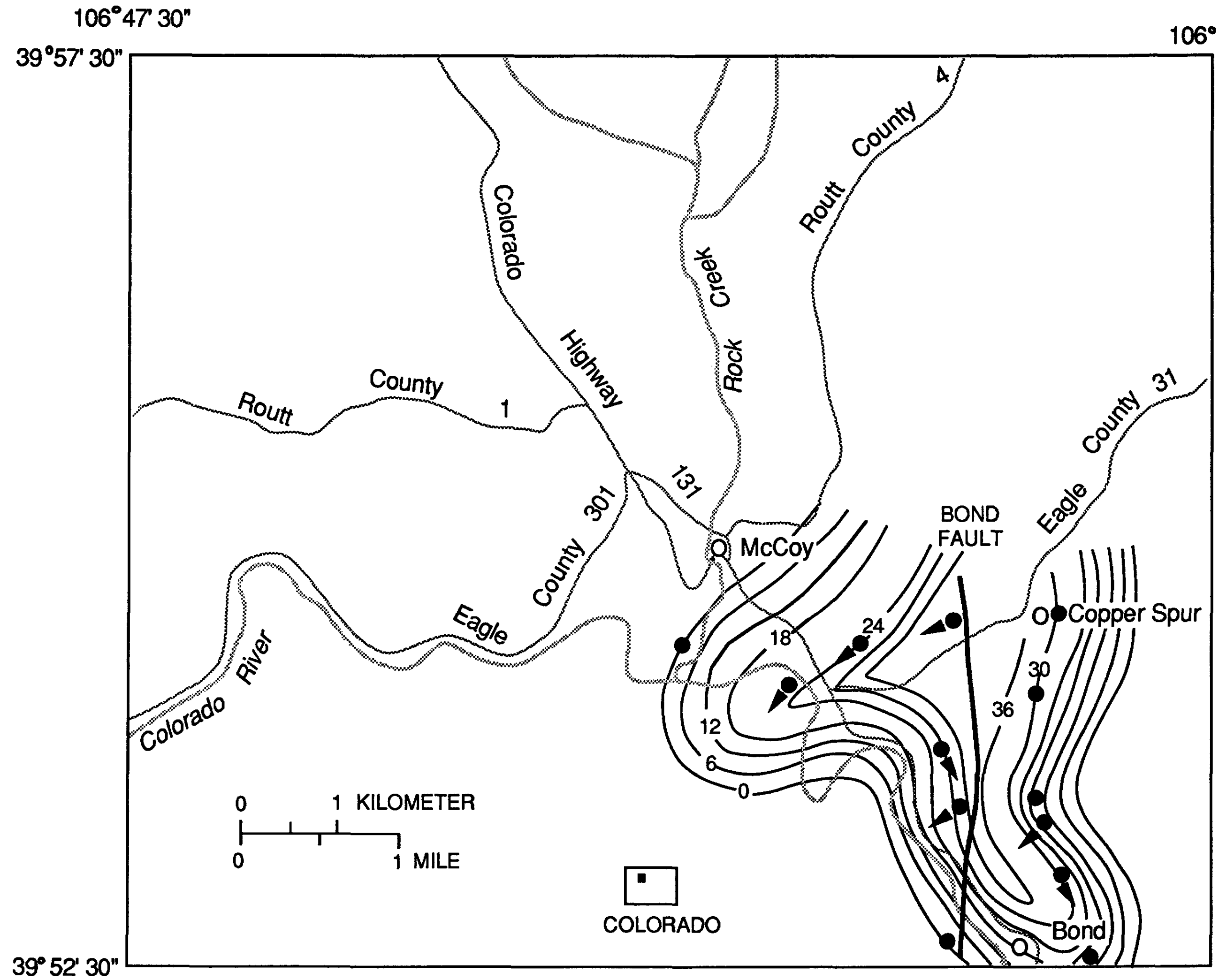


Figure 7. Isopach map showing thickness of turbidites and fluvial deposits in unit 5a. Paleocurrent vectors (solid arrows) compiled from measurements on current ripples and tool marks are also displayed. Rose diagrams for vectors are shown in appendix. Stratigraphic position of the unit is shown in figure 2. Contour interval 6 m. Solid circles indicate locations of measured sections.

conglomerates consist mostly of pebbles and cobbles in a coarse sandy and granular matrix. Trough crossbedding and planar bedding are the most common stratification types. In the western part of the study area, massive bedding and planar-tabular crossbedding are also common.

The deltas are lobate in plan view and contain large-scale (average thickness 13 m, 42 ft) planar-tangential foresets inclined at 20°–30°. The deltas are composed of granular, coarse-grained sandstone and are encased in siltstone. Paleocurrents were measured on both the fluvial and deltaic deposits using trough and planar-tabular crossbedding in the fluvial deposits and the large-scale, planar-tangential crossbedding of the delta foresets. The results show that fluvial currents were distributed radially around a north-south axis running through the western part of the area. The deltas also prograded to the south over the location those in the underlying marine interval in unit 5b (fig. 8). The trend of decreasing clast sizes from west to east (fig. 11) and the transition from a nonmarine to a marine environment also provide evidence that the main trunk stream lay in the western part of the area.

An isopach map of unit 6 (fig. 12) shows that the greatest accumulation of sediment (49 + m, 160 + ft) was in the western part of the study area, with thinning to the east. This trend is reversed west of Bond and Copper Spur, where a linear pattern of thicker sediment accumulation occurs. These patterns are consistent with progradation of a sediment wedge from the north, rather than from the east.

Studies of overlying units.—Studies of other units of the Minturn and Maroon Formations, overlying those discussed here, also provide evidence that the regional slope of the area was from north to south. T.R. Walker (University of Colorado) and J.C. Harms (Harms and Brady, Inc.) (written commun., 1985) showed that deltas in the western part of the McCoy-Bond area prograded to the southeast

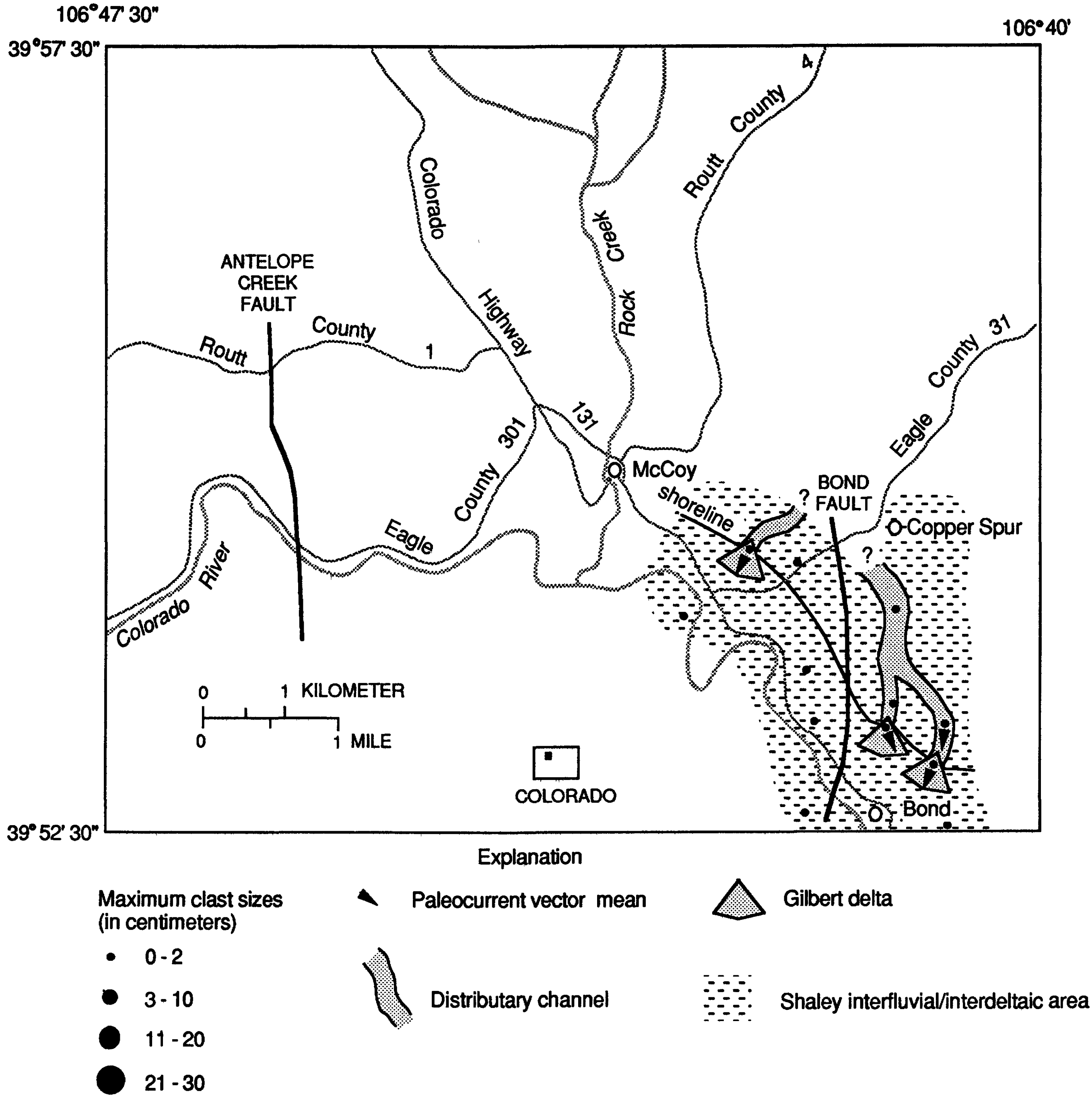


Figure 8. Paleocurrent directions and paleogeography during deposition of the lower part of unit 5b. Stratigraphic position of the unit is shown in figure 2. Rose diagrams for paleocurrent vectors are shown in appendix.

during deposition of unit 7 and to the south during deposition of unit 9. Stevens (1958), in reporting on distribution of marine limestone in the area, noted that marine limestones in units 13, 15, and 17 thin and decrease in fossil content to the north and east.

Johnson (1987), in studying fluvial sediments of the lower part of the Maroon Formation (overlying the Minturn), showed that a fluvial channel complex cropping out 1.6 km (1 mi) northwest of McCoy is oriented northeast-southwest and has a paleocurrent bearing of 228° (S. 48° W.). His estimate of the paleodischarge rate of the river associated with this channel is 417–1,250 m^3/sec, comparable to that of the modern South Platte River and "surprisingly large."

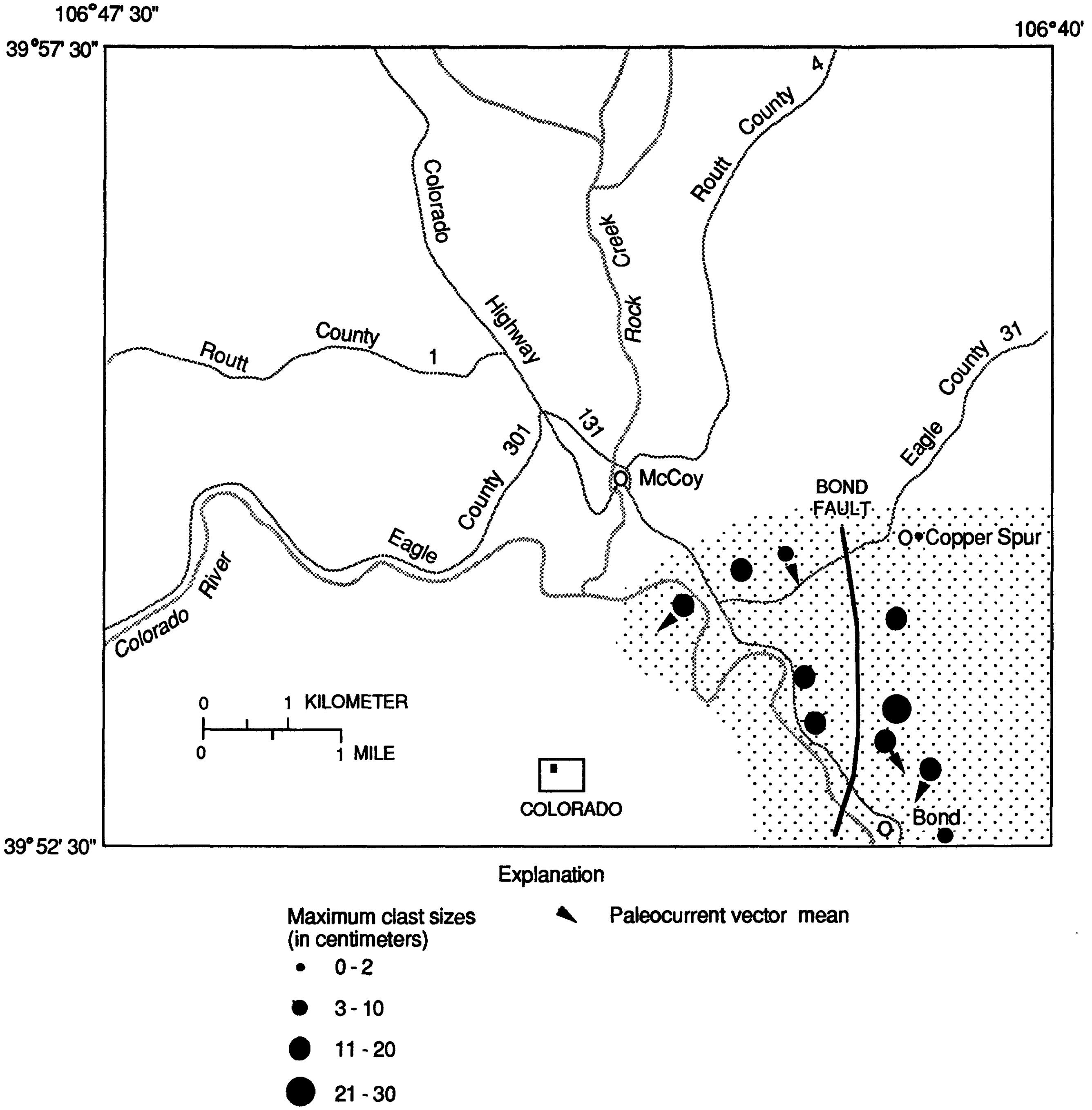


Figure 9. Paleocurrent vectors compiled from measurements made on fluvial deposits from the upper part of unit 5b. Stratigraphic position of the unit is shown in figure 2. Rose diagrams for paleocurrent vectors are shown in appendix.

Structural Influence on Paleocurrent Trends and Facies Patterns

The study area is near an en echelon offset in the fault zones thought to have bounded the eastern margin of the central Colorado basin. These areas of lateral offset between faults are known as transfer zones (Dahlstrom, 1969). They are recognized in both extensional (Crossley, 1984; Gibbs, 1984; Leeder and Gawthorpe, 1987; Leeder and others, 1988) and compressional (Dahlstrom, 1969, 1970) settings. They are described by Dahlstrom (1969) as "a kind of lap joint wherein the fault whose displacement is diminishing is replaced by an echelon fault whose displacement is increasing."

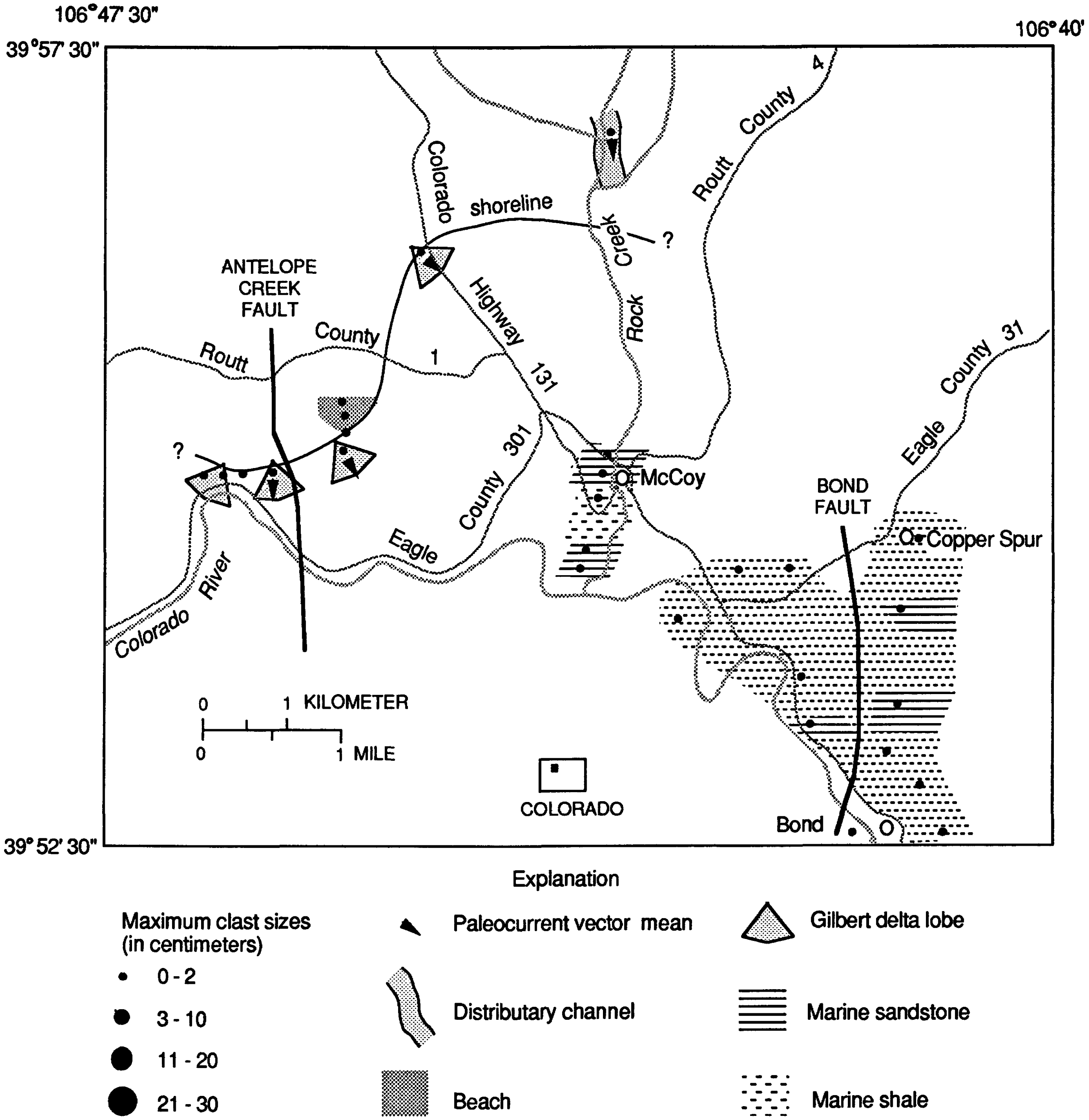


Figure 10. Paleocurrent directions and paleogeography during deposition of the lower part of unit 5c. Stratigraphic position of the unit is shown in figure 2. Rose diagrams for paleocurrent vectors are shown in appendix.

Transfer zones have important effects on the sedimentology of the basin fill. Fault-offset zones in the Malawi Rift Valley of Central Africa have large drainages developed on them that yield the greatest quantities of sediments to the rift basin (Crossley, 1984). The sediments accumulated at the bases of the transfer zones as "extensive sheets of coarse alluvium." The transfer zones may be underlain by transverse faults (Leeder and others, 1988).

Leeder and Gawthorpe (1987) also noted that large drainages tend to be developed along fault-offset zones in extensional settings. These drainages may extend far back into the hinterland, as a consequence of structural weakness in the offset zone.

The basin-margin faults of the Central Colorado basin in the McCoy-Bond area (that is, the Gore fault, unnamed northern fault, and unnamed transverse fault) were almost

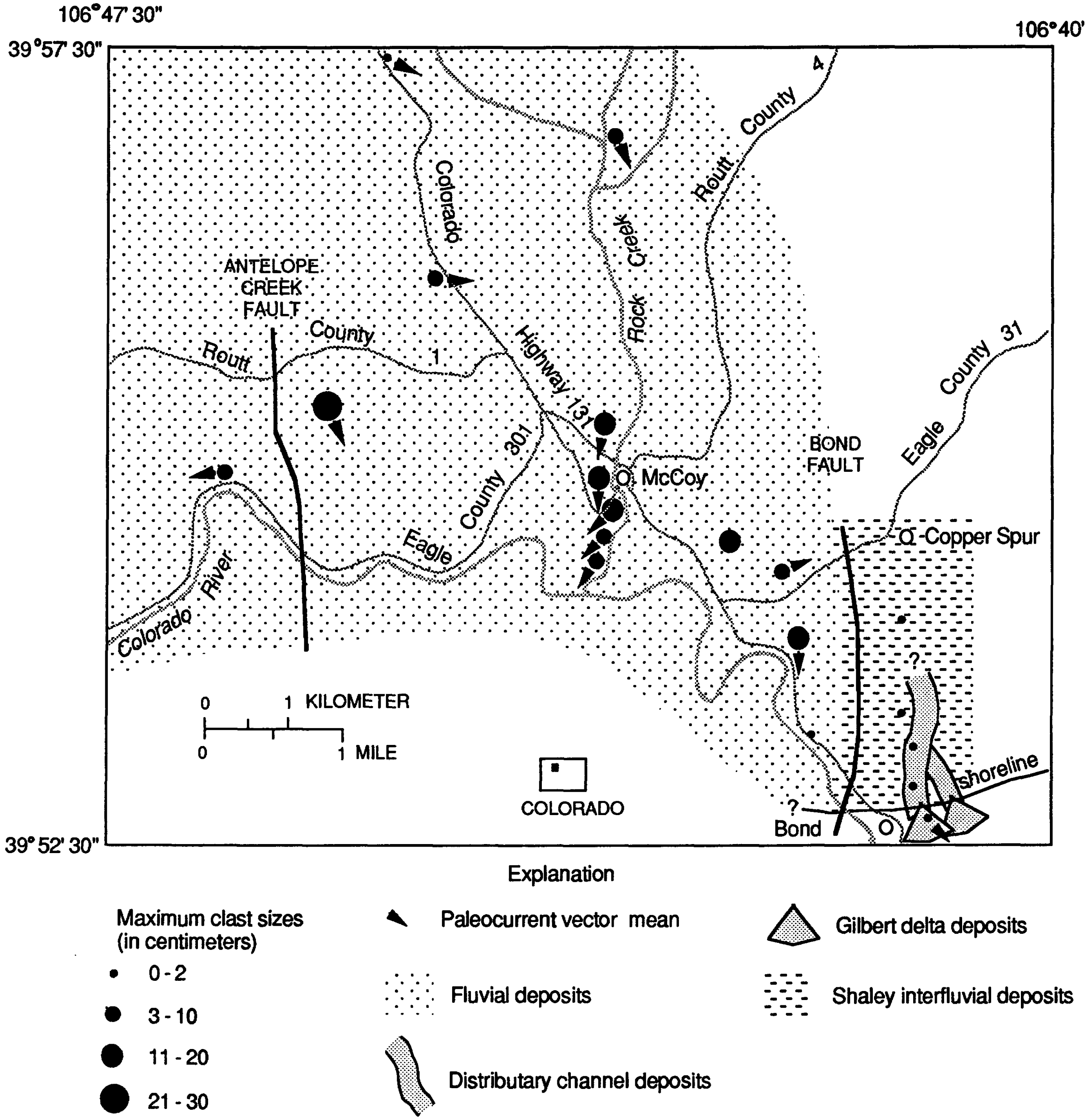


Figure 11. Paleocurrent directions and paleogeography during deposition of unit 6. Stratigraphic position of the unit is shown in figure 2. Rose diagrams for paleocurrents are shown in appendix.

certainly active during Pennsylvanian time. Thus, the Minturn Formation in this area was probably deposited at the base of a transfer zone. The presence of a transfer zone to the north of the study area would provide a zone of structural weakness and a topographic gradient necessary for development of south-flowing drainages. The surprisingly large size of the stream drainage noted by Johnson (1987) near McCoy may have been the result of an extensive drainage network developed to the north, along the dying trace of the Gore fault.

The concentration of deltas south of a line extending through McCoy and Copper Spur (figs. 8, 10, and 11) may also be a consequence of the transfer zone. The variety of marine and nonmarine deposits in each depositional cycle attests to fluctuations in relative sea-level position, yet only one Gilbert delta of the eighteen known from the area has

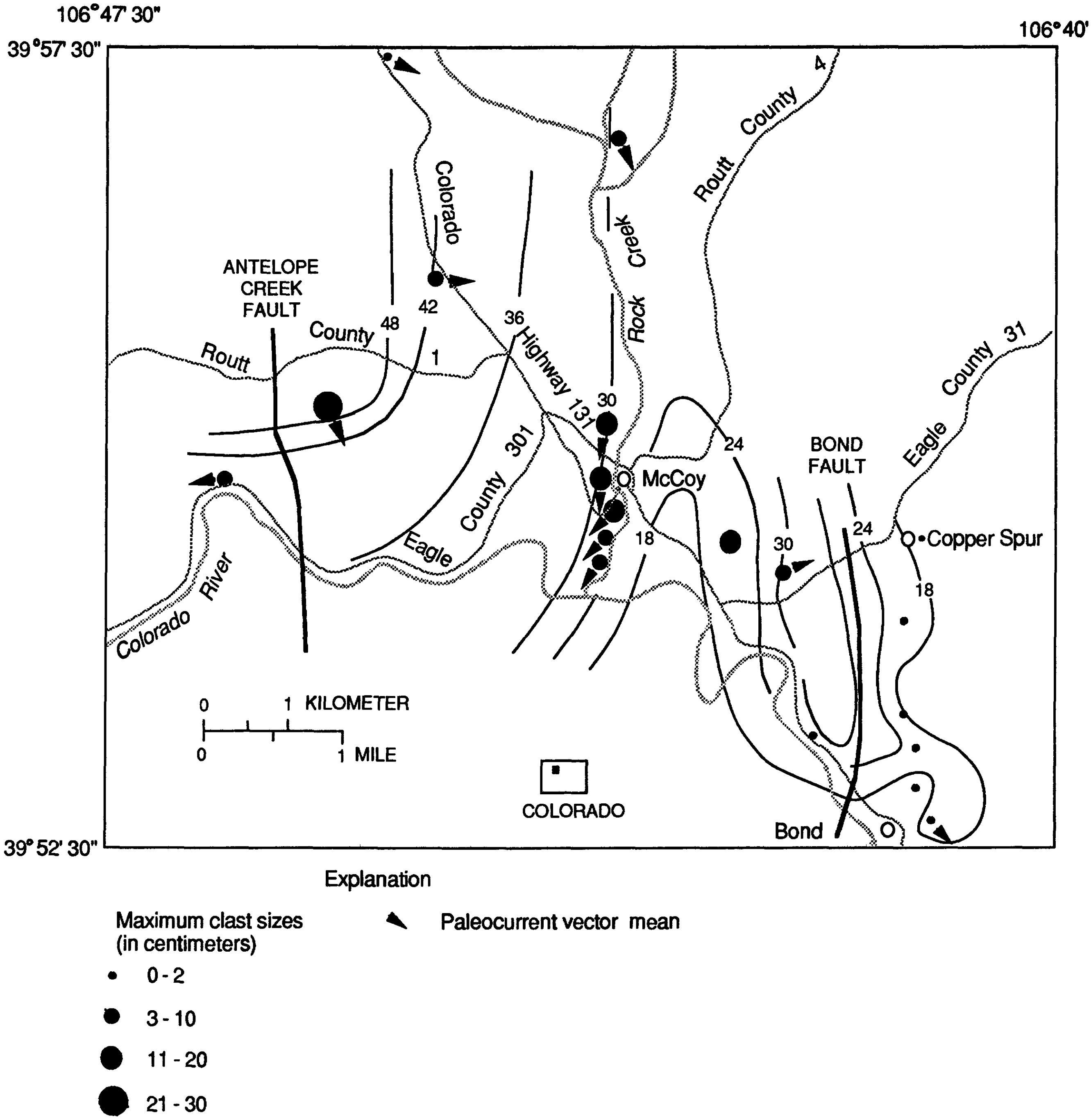


Figure 12. Isopach map showing the thickness of unit 6. Paleocurrent vectors from fluvial and deltaic deposits are shown for reference. Stratigraphic position of the unit is shown in figure 2. Contour interval 6 m.

been identified in outcrops at any horizon in the Minturn Formation north of the line through McCoy and Copper Spur. If the shoreline gradient were steep in this area, a large rise in sea level would be required to advance the shoreline any appreciable distance northward. Marine shorelines may have been repeatedly established in the area because the steep topographic gradient to the north did not permit further northward transgression. Southward-flowing drainages would have dropped their loads to form deltas repeatedly in approximately the same location.

A third consequence noted by Leeder and Gawthorpe (1987) is the presence of unusually large depocenters at the bases of transfer zones. The McCoy-Bond area, with its concentration of deltas and coarse fluvial deposits, may

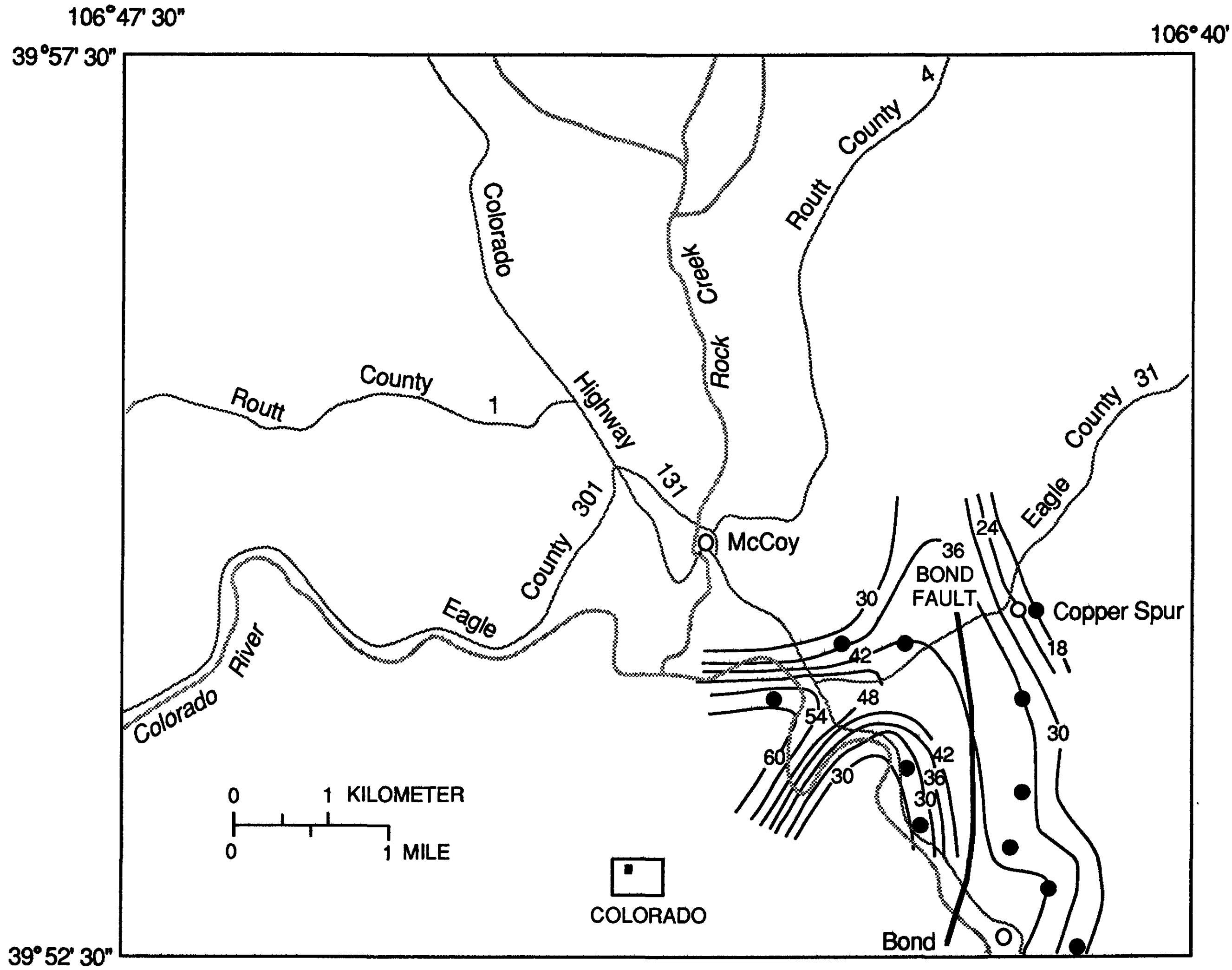


Figure 13. Isopach map showing the thickness of unit 5b. Stratigraphic position of the unit is shown in figure 2. Contour interval 6 m. Solid circles indicate locations of measured sections.

represent one of these large depocenters. Wood and Ethridge (1988) and Ethridge and Wescott (1984) suggested that braided fluvial and Gilbert delta deposits make excellent hydrocarbon reservoirs. Transfer zones such as that described for the McCoy-Bond area may thus be likely locations for multiple stacked reservoirs of unusually large size.

SEDIMENT DISTRIBUTIONS

Another unexpected result of the present study is the discovery that Minturn fluvial drainages in the McCoy-Bond study area were repeatedly established at the same locations. Because braided rivers have excessive sediment loads and shallow channels with unstable banks, avulsion occurs frequently (Miall, 1977), and broad braidplains may develop in the lower reaches of the rivers (McPherson and others, 1987). Braided fluvial sediments in the study interval are not distributed randomly over the study area; rather, the coarsest sediments are repeatedly restricted to the same geographic locations through several transgressive-regressive cycles. The intervening marine units also show a concentration of sand bodies, including Gilbert deltas and turbidites, at the same locations as the coarse fluvial deposits. Paleocurrents measured on the Gilbert deltas, turbidites, and fluvial deposits show a radial distribution about these sites of coarsest sediment accumulation. Two sequences can be used to illustrate these points.

Units 4, 5a, and 5b.—These units all show sediment dispersion about a north-south axis just west of Bond and Copper Spur (figs. 5–8). This axis coincides with the trace of a north-south-oriented basement fault (the Bond fault of Schmidt, 1961), along which an unnamed drainage presently flows. Pennsylvanian drainages also flowed along this axis; the isopach map (fig. 6) shows a large valley incised into unit 4 along the trace of the present-day Bond fault. It is not known whether a fault also underlies the drainage extending southwest from Copper Spur. Paleocurrent measurements made on tool marks and current ripples in the overlying turbidites show that turbidity currents also flowed down the incised channels (fig. 7).

This same area continued to be a site of coarse sediment accumulation during deposition of successive intervals. The overlying marine part of unit 5b, for example, contains three Gilbert deltas located over the sites of the two channels incised into unit 4 (fig. 8). Their paleocurrent directions coincide with those measured on the turbidites (fig. 7). Similarly, the braided fluvial deposits overlying these deltas (fig. 9) show the same dispersal patterns. An isopach map (fig. 13) of the marine and nonmarine deposits in unit 5b shows that, again, the thickest deposits are at the same locations as in unit 5a.

Units 5c, 6, and 7.—Following deposition of unit 5b, the axis of sediment dispersion shifted to the western part of the study area. The new axis is coincident with the trace of another north-south-oriented basement fault (herein referred to as the Antelope Creek fault) and a modern drainage, Antelope Creek (fig. 3).

After a marine transgression, Gilbert deltas prograded south and southeast from the axis along the trace of Antelope Creek fault. Five delta lobes were discovered in the western part of the study area (fig. 10), whereas in the eastern part only siltstone and thin sandstone beds were noted (fig. 10).

Overlying these deltas are coarse fluvial deposits of unit 6. This unit shows paleocurrents radiating outward from the trace of the present-day Antelope Creek fault (fig. 11). The area east of the Bond fault contains mostly sandstone and siltstone, and Gilbert deltas formed in the southeastern part of the study area.

An isopach map of units 5c and 6 (fig. 14) shows that the thickest accumulations of sediments are in the western part of the study area, though the area near the trace of the Bond fault also received more sediment than the immediately surrounding area. The area around McCoy, by

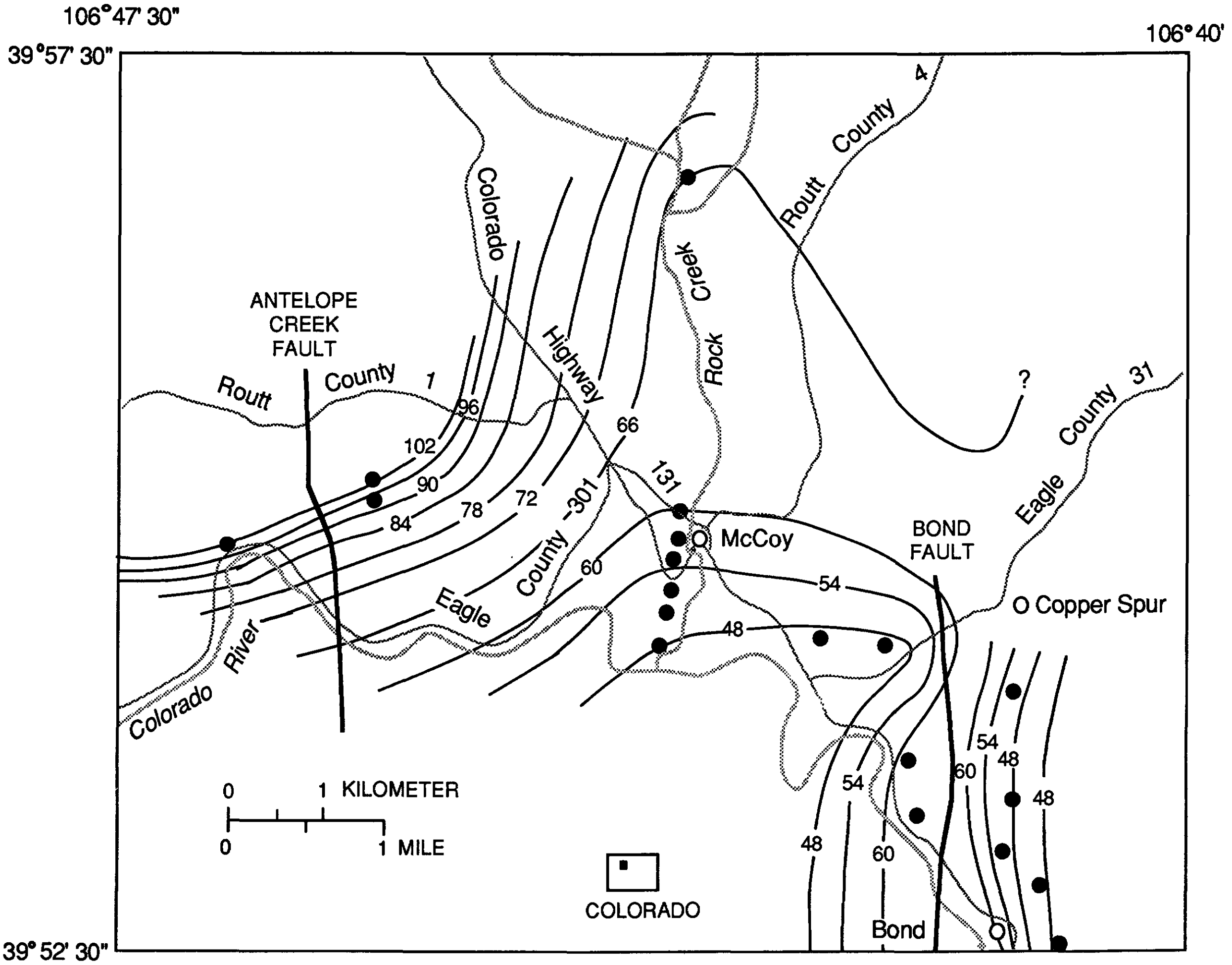


Figure 14. Isopach map showing the combined thickness of units 5c and 6. Stratigraphic position of the unit is shown figure 2. Contour interval 6 m. Solid circles indicate locations of measured sections.

contrast, contains thinner accumulations of units 5c and 6 and no accumulation of units 5a and 5b.

Unit 7 is a marine unit containing Gilbert deltas that were studied by T.R. Walker and J.C. Harms (written commun., 1985). At locations about 0.8 km (½ mi) east of Antelope Creek fault and 0.8 km (½ mi) north of the Colorado River, these workers discovered three lobes of a delta prograding to the east and southeast. This delta may also have been fed from paleodrainages following the trace of the Antelope Creek fault.

Structural Influence on Sediment Distributions

The repeated coincidence of stream drainages (and hence sites of delta progradation and turbidite deposition) and the traces of the Bond and Antelope Creek faults strongly suggests that these faults were active during deposition of the Minturn Formation. They exerted control on local sedimentation patterns by restricting drainages to specific paths and by increasing subsidence at specific locations.

DeVoto and others (1986, fig. 1) also inferred that the Bond and Antelope Creek faults were active in Pennsylvanian time, although they make no specific reference to them. Contemporaneous movement on the Bond and Antelope Creek faults during deposition of the Minturn Formation cannot, however, be directly confirmed. Modern valley incision and deposition do not permit direct observation of the faults where they pass through the study interval. These faults are two of several in the area that are present along the axes of folds associated with the Laramide orogeny. They are oriented parallel with the Gore fault zone, but their exact attitudes are not known. The Bond fault is exposed in a railroad cut southwest of Copper Spur (fig. 3); at this location the fault is essentially vertical. The Gore fault was also described as vertical by Tweto and Lovering (1977).

Thickness changes within the study interval provide indirect evidence for movement on the Bond and Antelope Creek faults during deposition of the Minturn Formation. A northwest-southeast cross section through these two faults (fig. 15) shows that the interval from the base of unit 3 to the top of unit 5b thickens substantially from 134 m (440 ft) near Antelope Creek fault to 207 m (680 ft) near the Bond fault and that units 5a and 5b are preserved only in the vicinity of the Bond fault. The interval containing units 5c and 6 shows the reverse relationship and thickens from 55 m (180 ft) near the Bond fault to 85 m (280 ft) near Antelope Creek fault. These thickness changes may have been the result of differential tilting and subsidence; the area east of the Bond fault subsided most rapidly during deposition of units 3 through 5b, and the area west of the Antelope Creek fault subsided most rapidly during deposition of units 5c and 6. The area between the two faults contains the thinnest sections and thus subsided most slowly.

The distribution of facies in the study area further supports this interpretation. Other workers have noted that structural lows tend to be sites of river channels, deltas, estuaries, and turbidites, whereas structural highs are interchannel and interdeltaic areas, shoals, and reefs (Allen, 1978; Bridge and Leeder, 1979; Weimer, 1986). These distributions are also evident in the Minturn Formation. Note, for example, the repeated occurrence of major fluvial channels, deltas, and turbidites near the Bond fault in units 5a, 5b, and 6 (figs. 6–9, 11, 12) and near Antelope Creek fault in units 5c and 6 (figs. 10–12). T.R. Walker and J.C. Harms (written commun., 1985) showed additional deltas near Antelope Creek fault in units 7 and 9. Also note that during deposition of units 3 through 5b the coarsest deposits were repeatedly concentrated near the Bond fault (figs. 4, 5, and 9). During deposition of units 5c and 6, coarse deposits were concentrated near the Antelope Creek fault (figs. 10, 11).

By contrast, it is noteworthy that deltas and turbidites are lacking in the outcrops around McCoy. The McCoy area received finer fluvial sediments during deposition of the nonmarine intervals. It was an interdeltaic area during deposition of most of the marginal-marine intervals and was the site of small carbonate buildups during deposition of marine intervals in units 3 and 5c.

If the Minturn Formation in the study interval were petroliferous (which it is not), structural control on facies distributions would cause the areas near the faults to be much better exploration targets than interfault areas. Near the faults a drill hole would likely encounter multiple stacked delta and channel deposits, whereas in an interdeltaic area a drill hole would probably encounter smaller fluvial channels and more shaley and carbonate facies.

An additional consequence of the structural control on facies distributions is that a vertical section measured at any location in the study area will not necessarily predict lateral relations accurately. An important qualification on Walther's Law is that facies belts must be able to migrate freely in order for all facies to be represented in a vertical section; however, structural control of drainage paths precludes free lateral migration of facies belts. Thus, any paleoenvironmental reconstruction based on a vertical section may omit laterally adjacent facies that are volumetrically significant.

The Bond and Antelope Creek faults can be related to other structural features along the eastern margin of the basin. They are the southernmost strands of the northern fault zone that forms the continuation of the eastern margin of the basin north of the transfer zone at McCoy (fig. 16). In the McCoy-Bond area, the thickest sections through the study interval are on the east side of the Bond fault. Workers in the Minturn and Avon areas, about 40 km (24 mi) to the southeast, also noted thickening of the Minturn Formation as they traced sections eastward toward the Gore fault zone

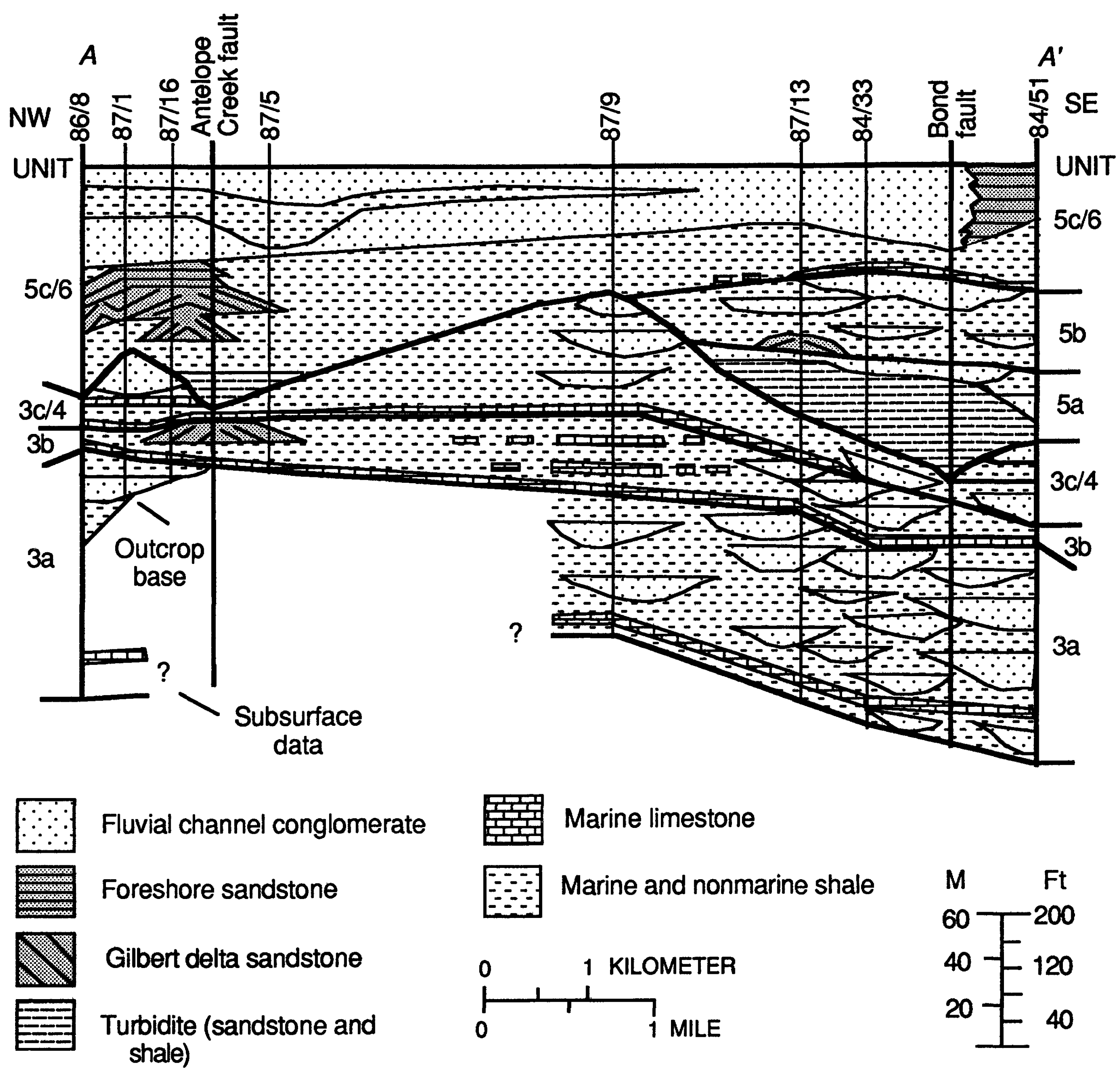


Figure 15. Northwest-southeast cross section showing units 3, 4, 5, and 6 of the Minturn Formation. Datum is base of unit 7. Heavy lines represent unit boundaries. Subsurface data are from Stevens (1958). Line of section shown in figure 3. Locations of measured sections (numbered) shown in appendix map.

(Boggs, 1966; Tillman, 1971; Walker, 1972; Schenk, 1989). This area of unusual thickness in the Minturn Formation was named the Vail-McCoy trough by Walker (1972).

By contrast, the area between the Bond and Antelope Creek faults received consistently thinner sediment accumulations during deposition of units 3 through 6. Schenk (1989) showed an area of thinner sediments to the south in the area around Edwards and Avon that he attributed to block faulting and differential subsidence associated with a structural high which he refers to as the Avon-Edwards high. He also showed an area of thicker sediment accumulation in the area around Eagle, about 40 km to the southwest, that he termed the Eagle sub-basin. Additional evidence for block-faulting within the central Colorado basin has been presented by Waechter and Johnson (1986) and Johnson and others (1990).

CONCLUSIONS

Study of the middle part of the Pennsylvanian Minturn Formation along the eastern margin of the Eagle basin

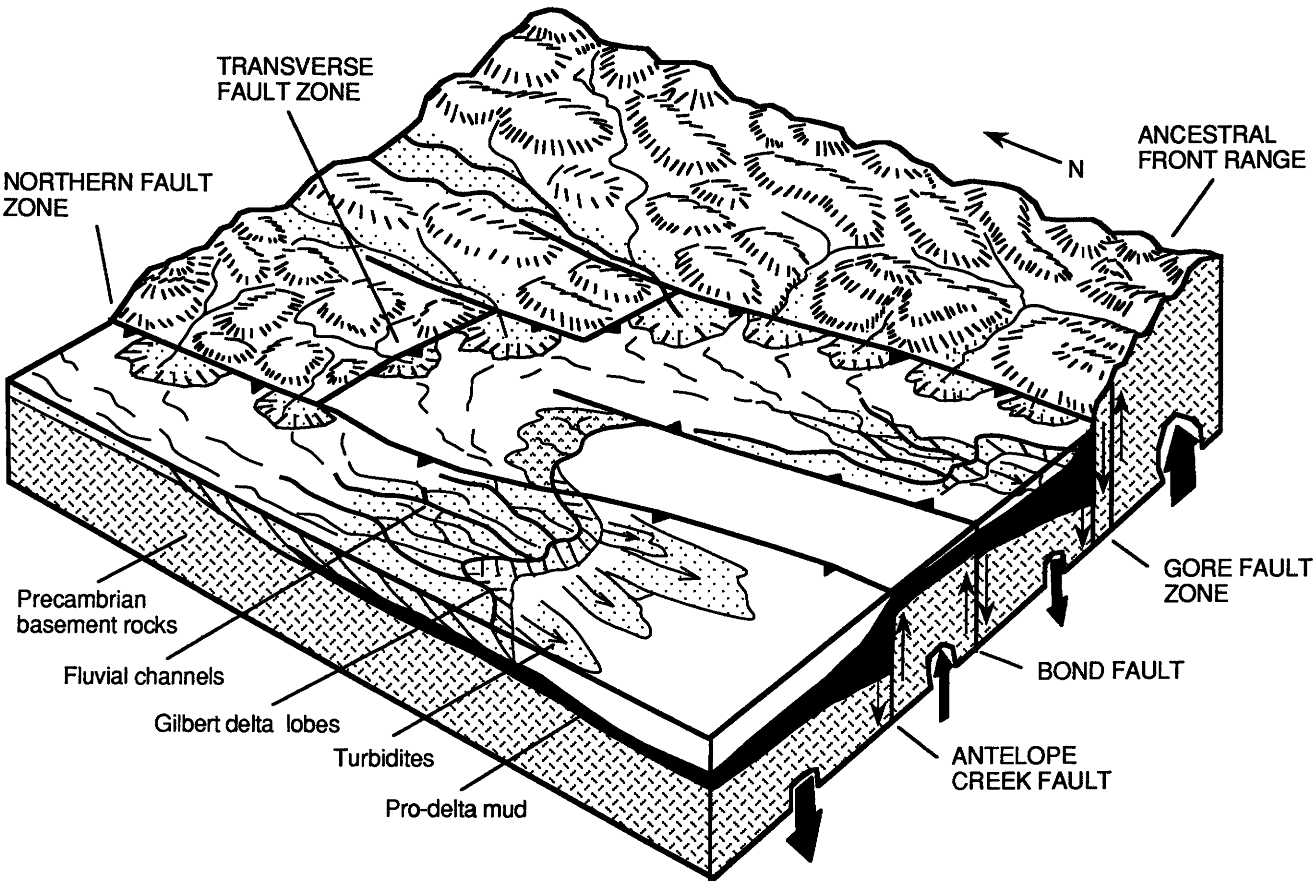


Figure 16. Block diagram showing the relationship between faults and sedimentary deposits in the study area during deposition of the Minturn Formation. Placement of faults is after Tweto (1976) and Tweto and others (1978). Teeth are on downthrown blocks, and heavy arrows show direction of relative movement during Pennsylvanian time. Top of block is approximately 32 by 40 km (20 by 25 mi).

has resulted in the following interpretations in regard to the relationship between structure and sedimentation in the area.

An en echelon offset in the bounding faults along the basin margin was a significant structural influence on sedimentation. Presence of a transfer zone may have caused the repeated southward orientation of stream drainages in the area and the concentration of shoreline sediments at the base of the zone in the southern part of the study area.

The southernmost strands of the basin margin fault to the north extended into the McCoy-Bond area and were active during deposition of the middle part of the Minturn Formation. The block east of the Bond fault subsided most rapidly during deposition of units 3 through 5b, and the block west of Antelope Creek fault subsided most rapidly during deposition of units 5c through 9. This subsidence caused the locations of major drainages, deltas, and turbidites to be restricted to the subsiding blocks, whereas the intervening upthrown block was the site of interdeltaic deposits and small carbonate buildups. This differential subsidence caused thicker and more complete sections to be preserved east of the Bond fault and west of the Antelope Creek fault and thinner, less complete sections to be preserved on the intervening block.

The fault-bounded blocks in the study area are similar in structural style to the Vail-McCoy trough of Walker (1972) and Schenk (1989) and the Avon-Edwards high and Eagle sub-basin of Schenk (1989).

REFERENCES CITED

Allen, J.R.L., 1978, Studies in fluviatile sedimentation—An exploratory quantitative model for the architecture of avulsion-controlled alluvial suites: Sedimentary Geology, v. 21, p. 129–147.

Beerbower, J.R., 1964, Cyclothems and cyclic depositional mechanisms in alluvial plain sedimentation, *in* Merriam, D.F., ed., Symposium on cyclic sedimentation: Kansas Geological Survey Bulletin 169, v. 1, p. 31–42.

Boggs, Sam, Jr., 1966, Petrology of the Minturn Formation, east-central Eagle County, Colorado: American Association of Petroleum Geologists Bulletin, v. 50, p. 1399–1422.

——— 1987, Principles of sedimentology and stratigraphy: Columbus, Ohio, Merrill, 784 p.

Bridge, J.S., and Leeder, M.R., 1979, A simulation model of alluvial stratigraphy: Sedimentology, v. 26, p. 617–644.

Chronic, John, and Stevens, Calvin, 1958, Pennsylvanian paleogeography in the McCoy area, Eagle County, *in* Curtis, B.F., ed., Symposium on Pennsylvanian rocks of Colorado and adjacent areas: Rocky Mountain Association of Geologists, p. 86–90.

Crossley, R., 1984, Controls on sedimentation in the Malawi rift valley, Central Africa: Sedimentary Geology, v. 40, p. 33–50.

Dahlstrom, C.D.A., 1969, Balanced cross sections: Canadian Journal of Earth Sciences, v. 6, p. 743–757.

——— 1970, Structural geology in eastern margin of Canadian Rocky Mountains [abs.]: American Association of Petroleum Geologists Bulletin, v. 54, no. 5, p. 843.

DeVoto, R.H., 1972, Pennsylvanian and Permian stratigraphy and tectonism in central Colorado: Colorado School of Mines Quarterly, v. 67, no. 4, p. 139–185.

——— 1980, Pennsylvanian stratigraphy and history of Colorado, *in* Kent, H.C., and Porter, K.W., eds., Colorado geology: Rocky Mountain Association of Geologists, p. 71–101.

DeVoto, R.H., Bartleson, B.L., Schenk, C.J., and Waechter, N.B., 1986, Late Paleozoic stratigraphy and syndepositional tectonism, northwestern Colorado, *in* Stone, D.S., ed., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, p. 37–50.

Ethridge, F.G., and Wescott, W.A., 1984, Tectonic setting, recognition, and hydrocarbon reservoir potential of fan-delta deposits, *in* Koster, E.H., and Steel, R.J., eds., Sedimentology of gravels and conglomerates: Canadian Society of Petroleum Geologists Memoir, v. 10, p. 217–235.

Gibbs, A.D., 1984, Structural evolution of extensional basin margins: Geological Society of London Journal, v. 141, p. 609–620.

Gilbert, G.K., 1885, The topographic features of lake shores: U.S. Geological Survey 5th Annual Report, p. 69–123.

Houck, K.J., and Lockley, M, 1986, Pennsylvanian biofacies of the Central Colorado Trough: University of Colorado–Denver, Geology Department Magazine, Special Issue 2, 64 p.

Johnson, S.Y., 1987, Sedimentology and paleogeographic significance of six fluvial sandstone bodies in the Maroon Formation, Eagle Basin, northwest Colorado: U.S. Geological Survey Bulletin 1787–A, 17 p.

Johnson, S.Y., Schenk, C.J., Anders, D.E., and Tuttle, M.L., 1990, Sedimentology and petroleum occurrence, Schoolhouse Member, Maroon Formation (Lower Permian), northwestern Colorado: American Association of Petroleum Geologists Bulletin, v. 74, no. 2, p. 135–150.

Kluth, C.F., 1986, The plate tectonics of the Ancestral Rocky Mountains, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region: American Association of Petroleum Geologists Memoir 41, p. 353–370.

Leeder, M.R., 1978, A quantitative stratigraphic model for alluvium, with special reference to channel deposit density and interconnectedness, *in* Miall, A.D., ed., Fluvial sedimentology: Canadian Society of Petroleum Geologists Memoir 5, p. 587–596.

Leeder, M R., and Gawthorpe, R.L., 1987, Sedimentary models for extensional tilt-block/half-graben basins, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental extensional tectonics: Geological Society of London Special Publication 28, p. 139–152.

Leeder, M.R., Ord, D.M., and Collier, R., 1988, Development of alluvial fans and fan deltas in neotectonic extensional settings—Implications for the interpretation of basin-fills, *in* Nemec, W., and Steel, R.J., eds., Fan deltas—Sedimentology and tectonic settings: Glasgow, Blackie and Son, p. 173–185.

Mallory, W.W., 1972, Regional synthesis of the Pennsylvanian System, *in* Mallory, W.W., ed., Geologic atlas of the Rocky Mountain region: Rocky Mountain Association of Geologists, p. 111–127.

McPherson, J.G., Shanmugam, G., and Moiola, R.J., 1987, Fan-deltas and braid deltas; varieties of coarse-grained deltas: Geological Society of America Bulletin, v. 99, p. 331–340.

Miall, A.D., 1977, A review of the braided-river depositional environment: Earth Science Reviews, v. 13, p. 1–62.

Molnar, P., and Tapponier, P., 1975, Cenozoic tectonics of Asia; effects of a continental collision: Science, v. 189, p. 419–426.

Schenk, C.J., 1989, Sedimentology and stratigraphy of the Eagle Valley Evaporite (Middle Pennsylvanian), Eagle Basin, northwest Colorado: Boulder, University of Colorado, Ph.D. thesis, 172 p.

Schmidt, P.B., 1961, The geology of the State Bridge area, Colorado: Boulder, University of Colorado, M.A. thesis, 67 p.

Stevens, C.H., 1958, Stratigraphy and paleontology of the McCoy, Colorado, area: Boulder, University of Colorado, M.A. thesis, 242 p.

Tillman, R.W., 1971, Petrology and paleoenvironments, Robinson Member, Minturn Formation (DesMoinesian), Eagle Basin, Colorado: American Association of Petroleum Geologists Bulletin, v. 55, p. 593–620.

Tweto, Ogden, compiler, 1976, Geologic map of the Craig 1°×2° quadrangle, northwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–972, scale 1:250,000.

——— 1977, Tectonic history of west-central Colorado, *in* Veal, H.K., ed., Exploration frontiers of the central and southern Rockies: Rocky Mountain Association of Geologists Field Conference Guidebook, p. 11–22.

——— 1980, Tectonic history of Colorado, *in* Kent, H.C., and Porter, K.W., Colorado geology: Rocky Mountain Association of Geologists, p. 5–9.

Tweto, Ogden, and Lovering, T.S., 1977, Geology of the Minturn 15-minute quadrangle, Eagle and Summit Counties, Colorado: U.S. Geological Survey Professional Paper 956, 96 p.

Tweto, Ogden, Moench, R.H., and Reed, J.C., Jr., 1978, Geologic map of the Leadville 1°×2° quadrangle, northeastern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–999, scale 1:250,000.

Waechter, N.B., and Johnson, W.E., 1986, Pennsylvanian-Permian paleostructure and stratigraphy as interpreted from seismic data in the Piceance Basin, northwest Colorado, *in* Stone, D.S., ed., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, p. 51–64.

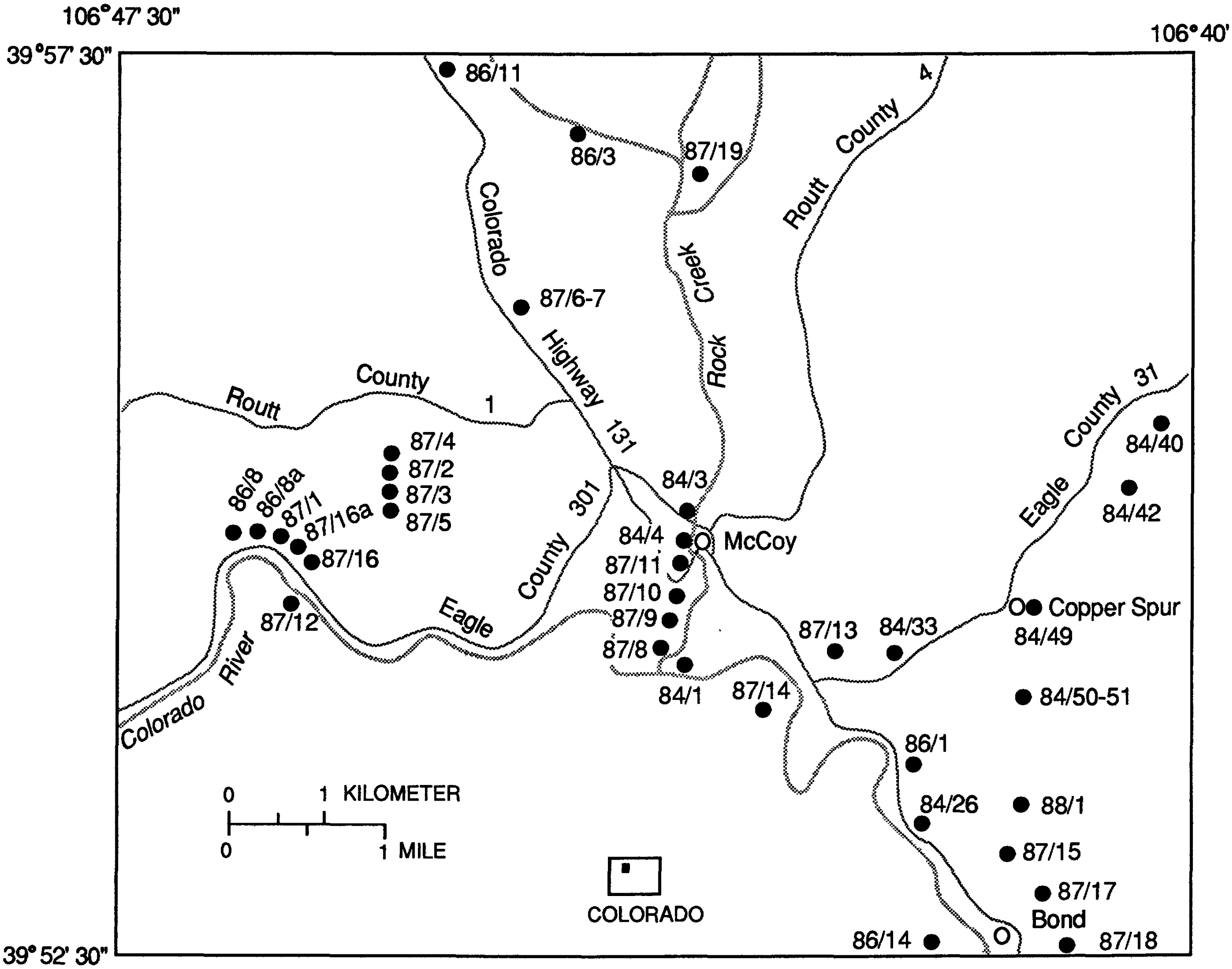
Walker, T.R., 1972, Bioherms in the Minturn Formation (Des-Moinesian age), Vail-Minturn area, Eagle County, Colorado: Colorado School of Mines Quarterly, v. 67, no. 4, p. 249–278.

Weimer, R.J., 1986, Relationship of unconformities, tectonics, and sea level changes in the Cretaceous of the Western Interior, United States, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region: American Association of Petroleum Geologists Memoir 41, p. 397–422.

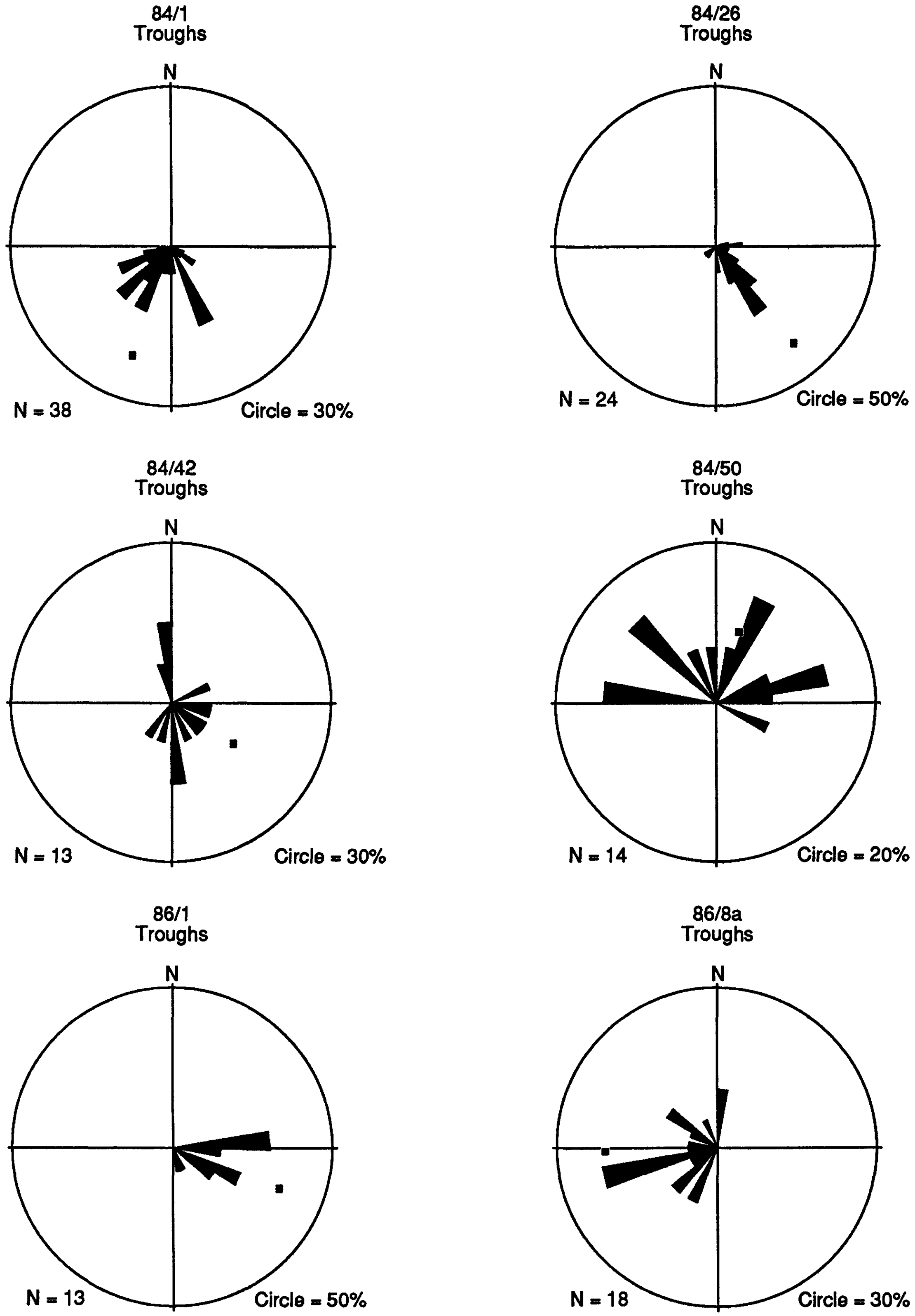
Wood, M.L., and Ethridge, F.G., 1988, Sedimentology and architecture of Gilbert- and mouth bar-type deltas, Paradox Basin, Colorado, *in* Nemec, W., and Steel, R.J., Fan deltas—Sedimentology and tectonic settings: Glasgow, Blackie and Son, p. 250–263.

APPENDIX—ROSE DIAGRAMS FOR DEPOSITIONAL UNITS OF THE MINTURN FORMATION

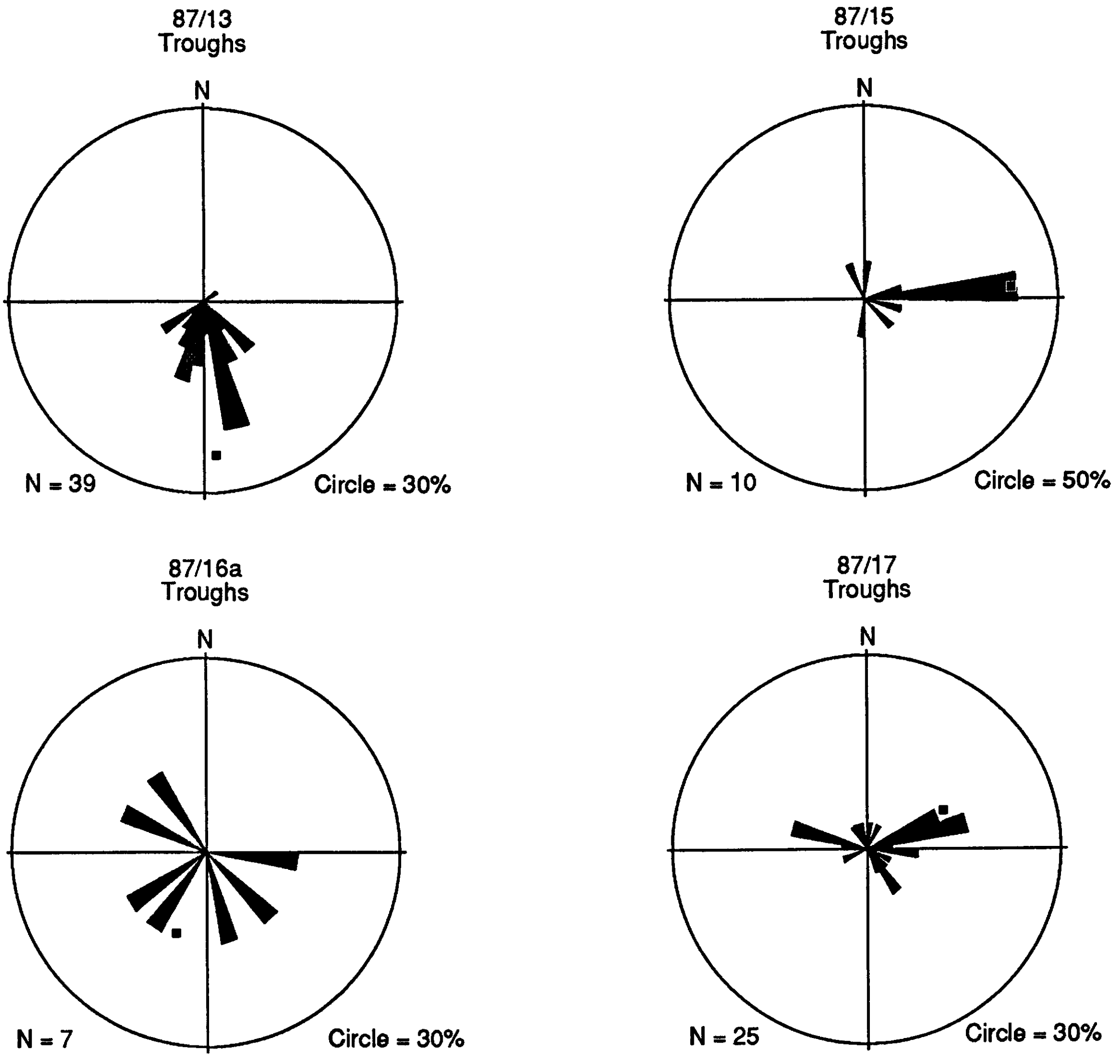
Data for each paleocurrent arrow on the maps (text figs. 4–12) are shown as rose diagrams. The diagrams are grouped by units, and the unit numbers are given at the top of each set of diagrams (see also text fig. 2). Location numbers are given for each diagram; see the map that immediately follows for locations of measured sections (shown as solid circles on map). The number of measurements is given in the lower left below each diagram, and the percentage value of the outer perimeter (in relation to the entire data set) is given in the lower right. The trend and plunge of the mean paleocurrent vector for each data set is shown as a small black square.



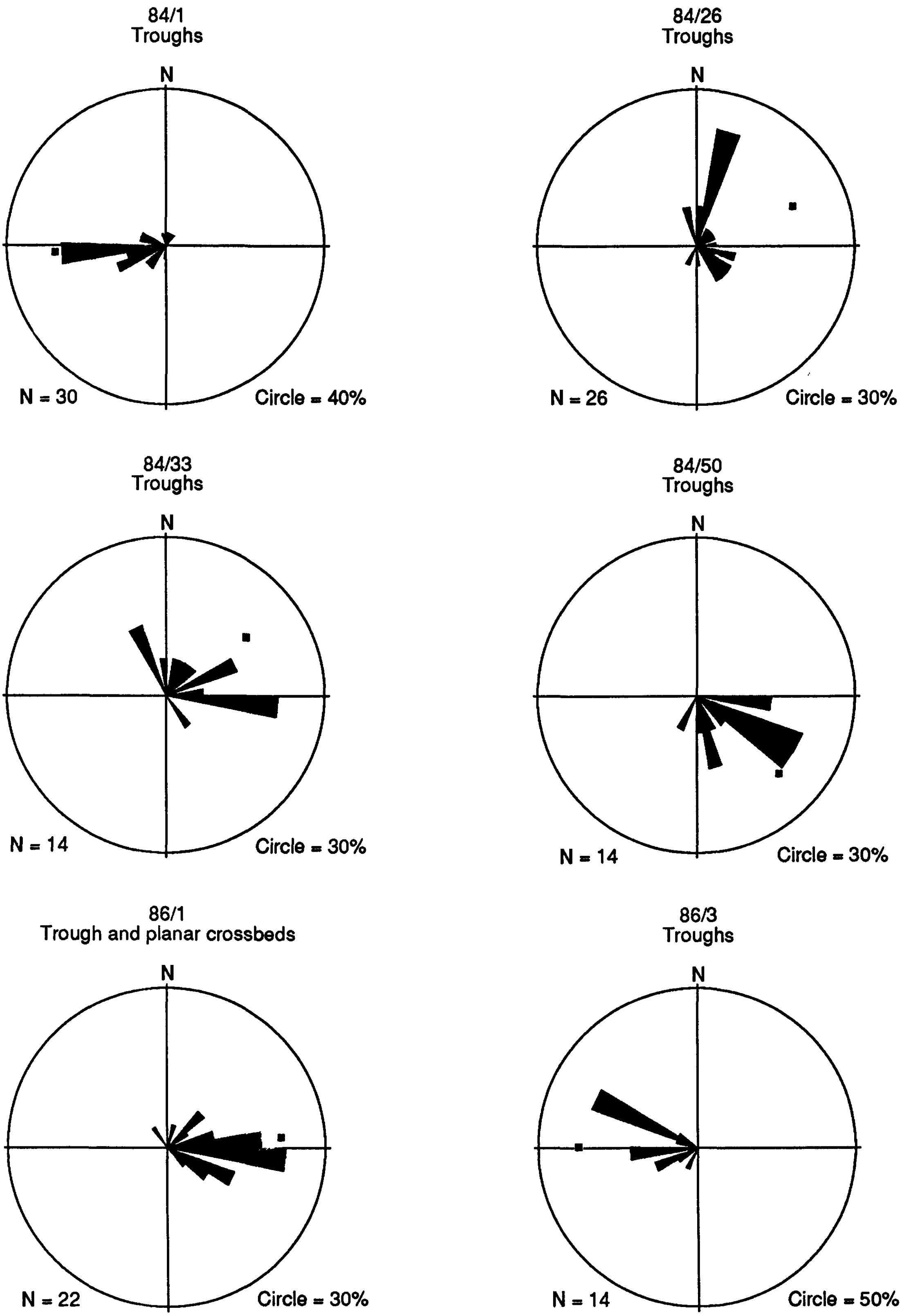
Fluvial Deposits, Upper Part of Unit 3a



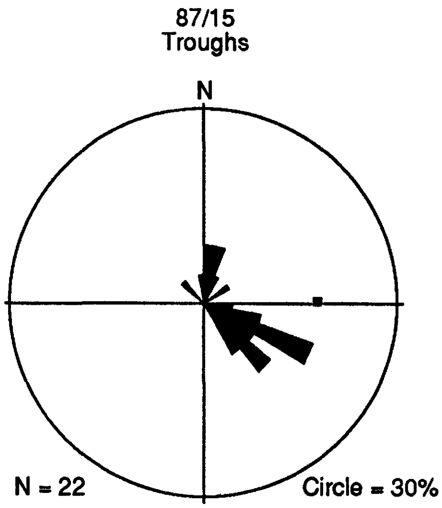
Fluvial Deposits, Upper Part of Unit 3a

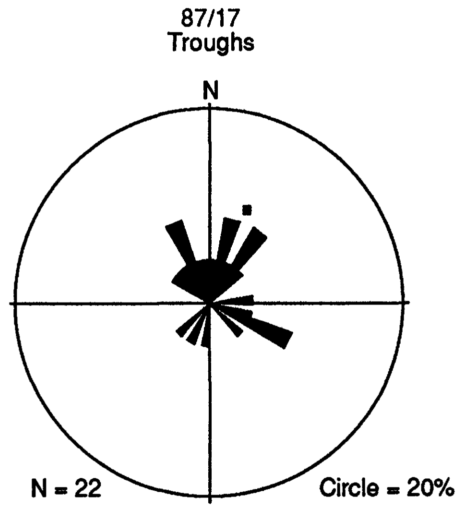


Fluvial Deposits, Unit 4

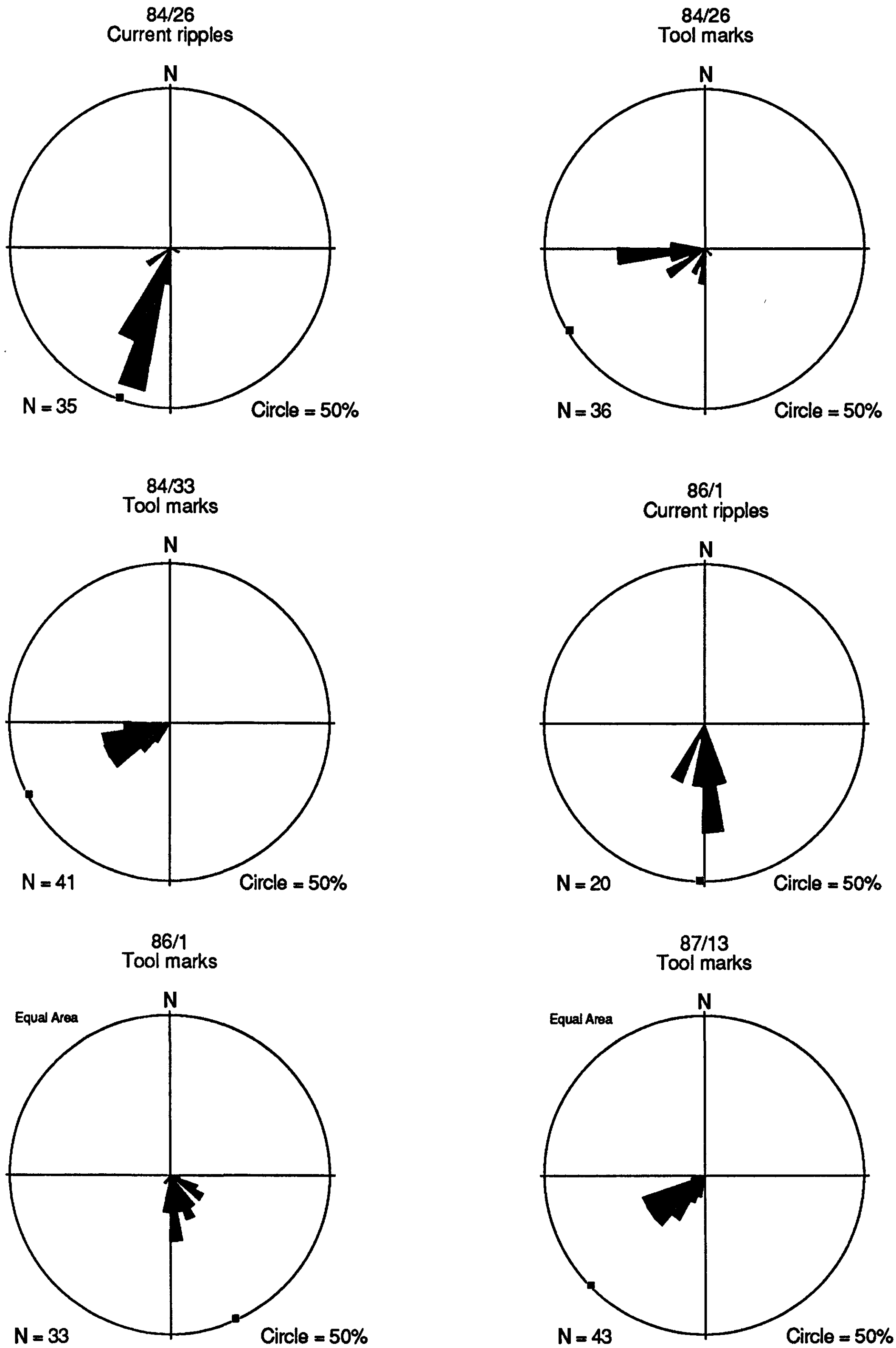


Fluvial Deposits, Unit 4



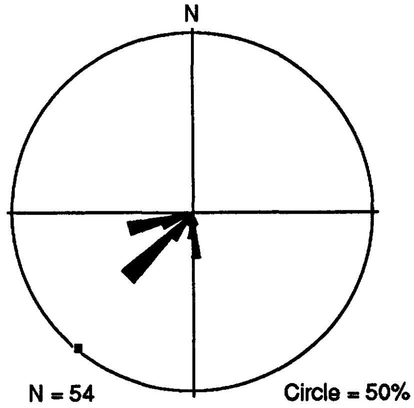


Turbidites, Lower Part of Unit 5a

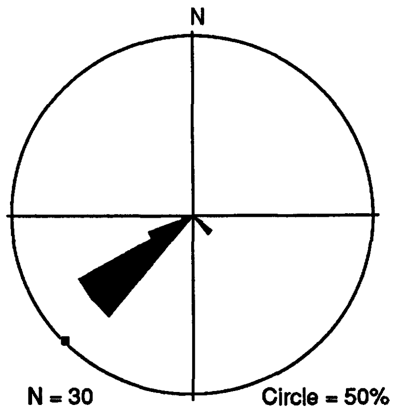


Turbidites, Lower Part of Unit 5a

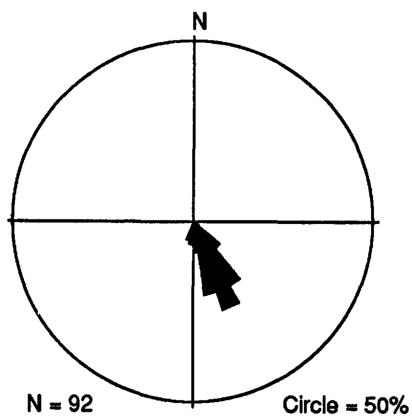
87/14
Tool marks



87/15
Tool marks

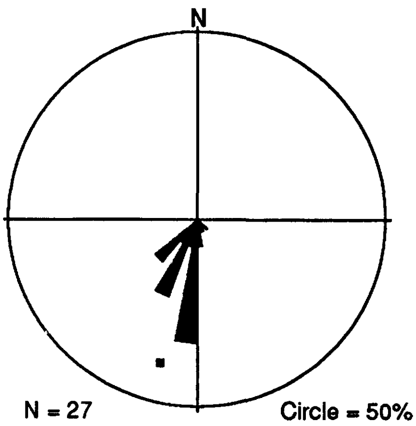


87/17
Tool marks

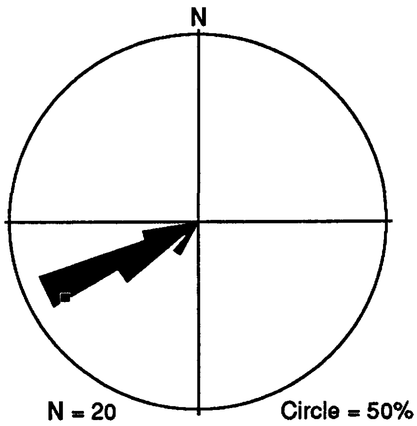


Delta Deposits, Lower Part of Unit 5b

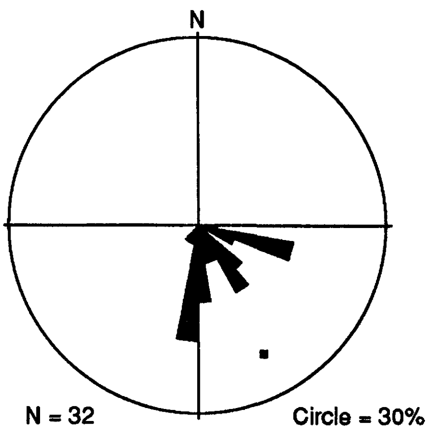
87/13
Large planar foresets



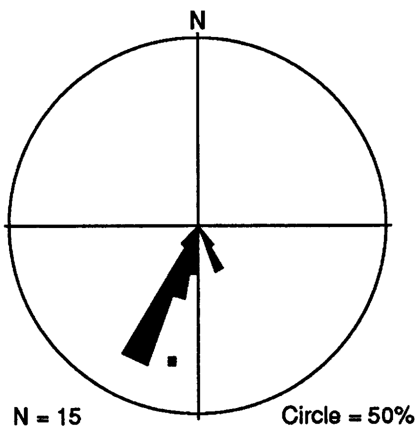
87/14
Large planar foresets



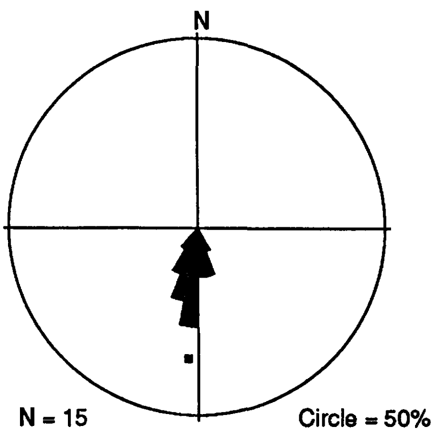
87/15
Large planar foresets



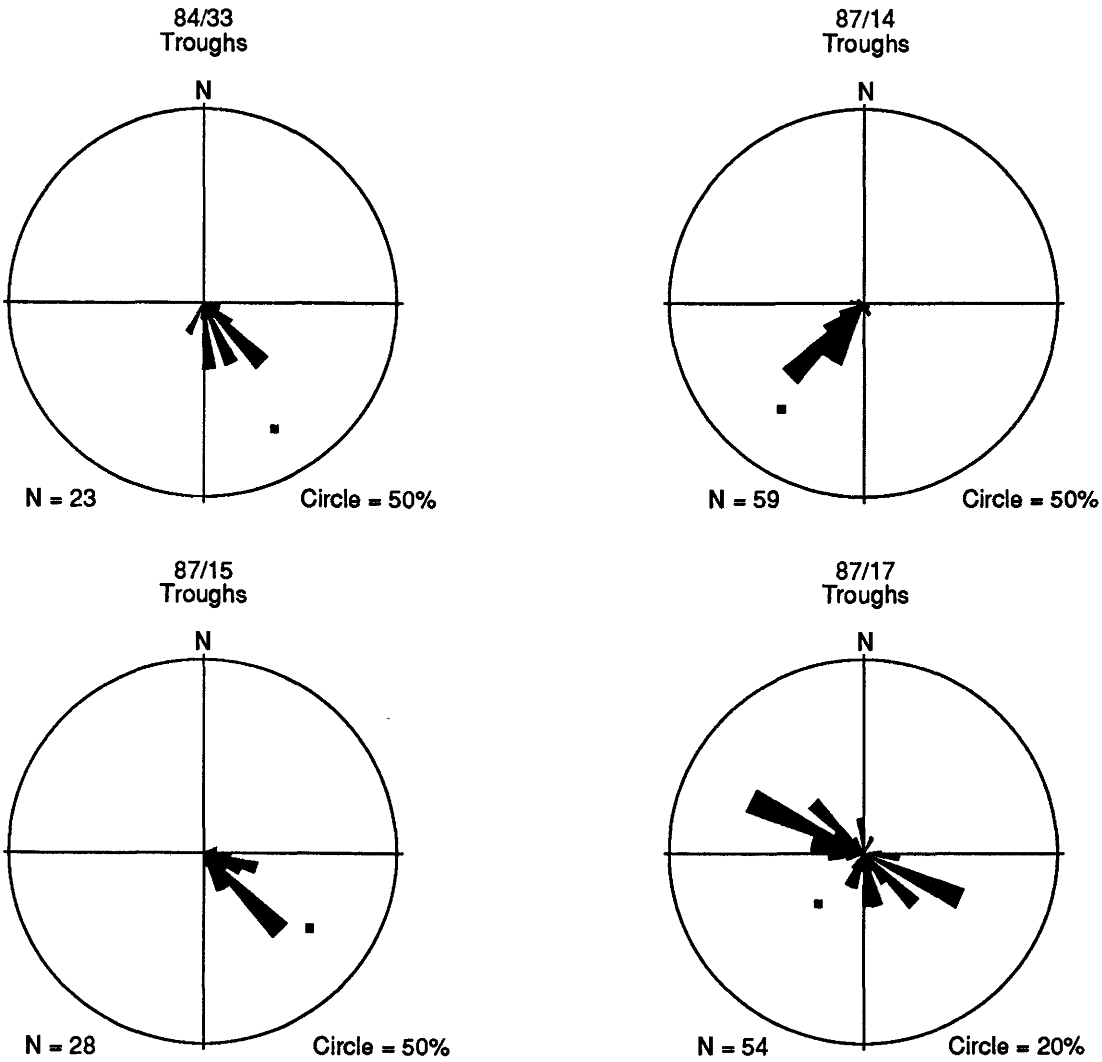
87/17
Large planar foresets



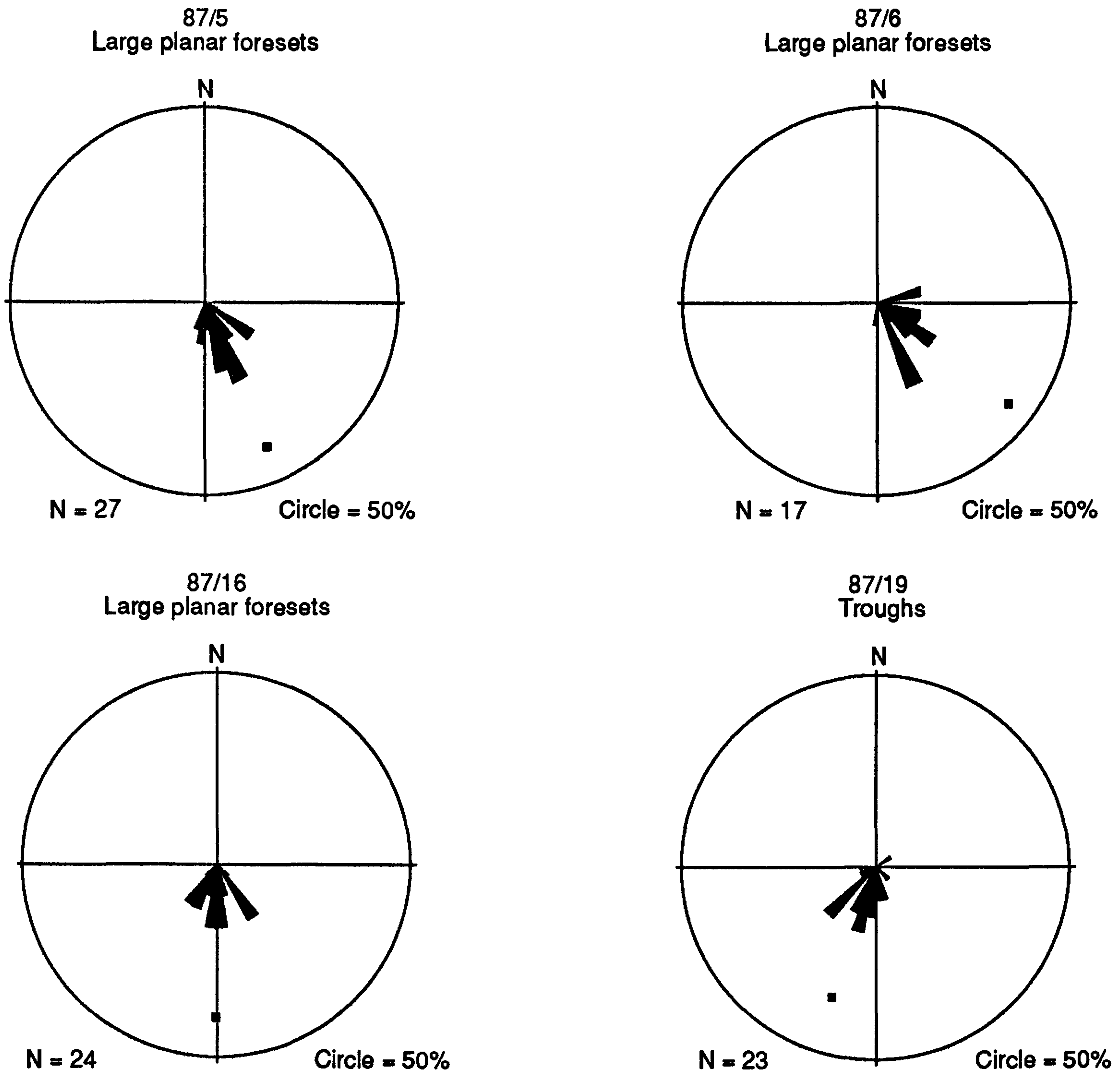
87/17
Troughs



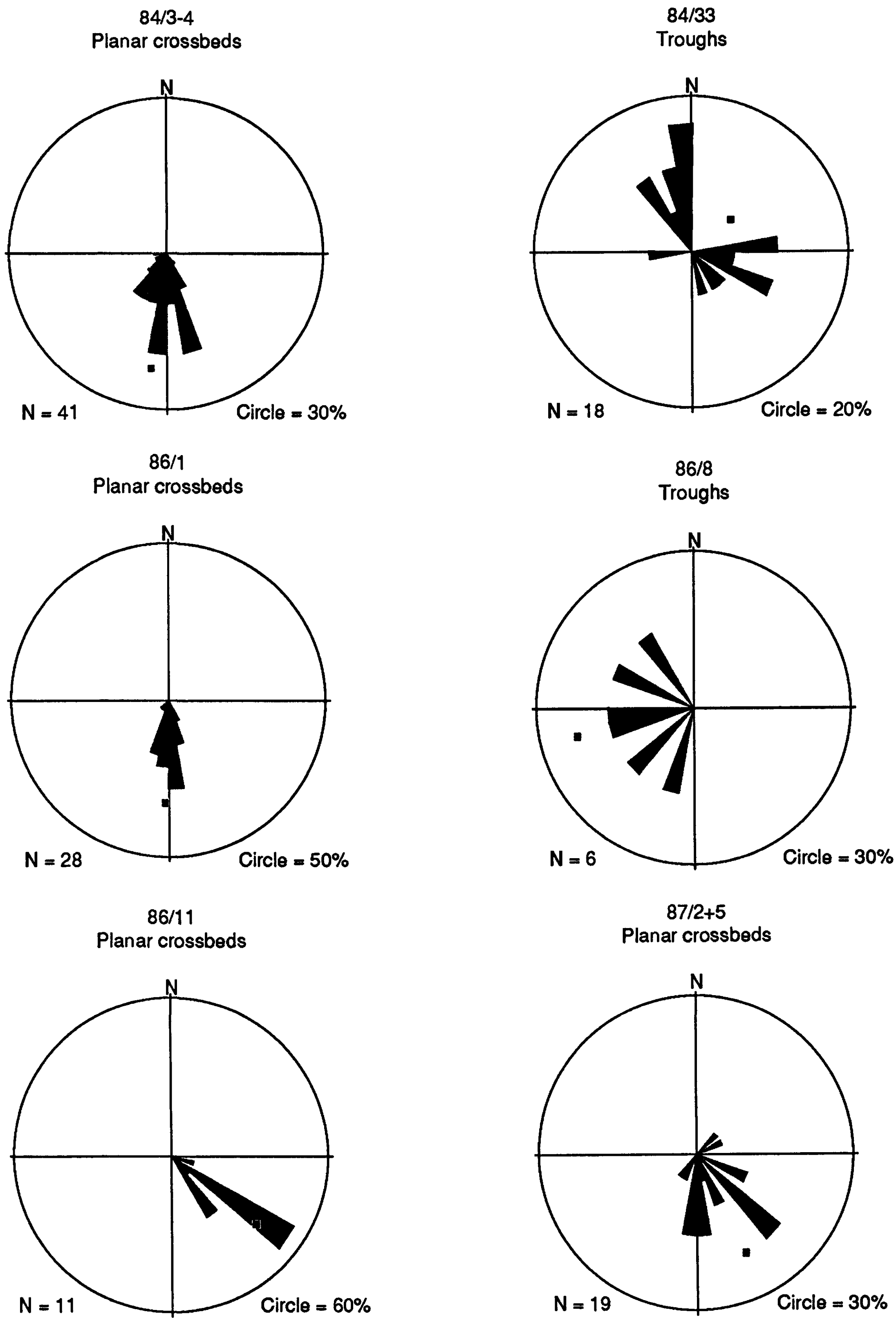
Fluvial Deposits, Upper Part of Unit 5b

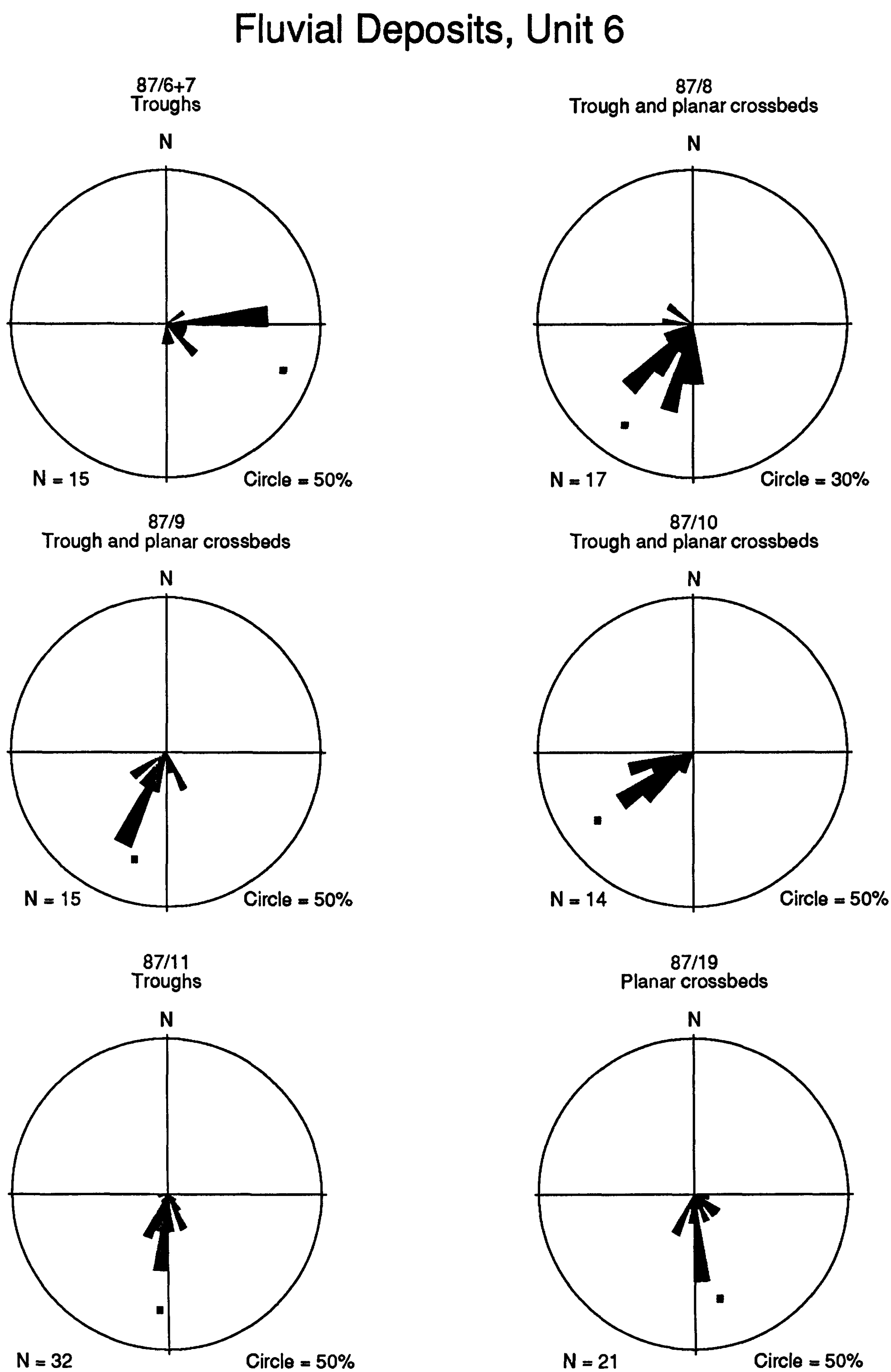


Delta Deposits, Lower Part of Unit 5c



Fluvial Deposits, Unit 6





☆U.S. GOVERNMENT PRINTING OFFICE: 1991-573-049/46009

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000 and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879- 1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962- 1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971- 1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.--Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.

U.S. DEPARTMENT OF THE INTERIOR

March 3, 1849