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Horizontal-Stress Directions in the Denver and Illinois Basins from the Orientations of Borehole Breakouts

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HORIZONTAL-STRESS DIRECTIONS IN THE DENVER AND ILLINOIS BASINS FROM THE ORIENTATIONS OF BOREHOLE BREAKOUTS

By Richard Dart

ABSTRACT

Theoretical and field studies by previous workers have indicated that compressive stresses concentrated at the borehole wall can induce failure of the wall rock, resulting in enlargement (breakout) of the well bore in the direction of minimum horizontal stress (S_h). Using dipmeter and fracture identification well-log data, orientations of borehole breakouts were determined for selected wells in the Denver and Illinois Basins. Directions of S_h were inferred from azimuths of breakout from 5 wells in the west-central portion of the Denver Basin and 17 wells in the south-central portion of the Illinois Basin.

Assuming breakout orientations to be reliable stress indicators, mean directions of S_h and mean angular deviation were calculated for individual wells and collectively for each basin. Mean directions of S_h from totals of feet of breakout and number of breakouts for the Denver Basin are N. 73° E. and N. 76° E., respectively, and for the Illinois Basin are N. 2° W. and N. 0°, respectively. These orientations of S_h generally agree with published stress data for the two regions.

INTRODUCTION

In areas where data from hydraulic fracturing, overcoring, earthquake focal mechanisms, and geologic indicators of regional stress are inconclusive or not available, the orientations of well-bore breakouts could provide information on the regional stress field in areas where sufficient well-log data are available. In recent years, a number of studies using borehole breakouts as stress indicators were carried out in the following areas: Alberta and the Northwest Territories of Canada (Cox, 1970; Babcock, 1978; Bell and Gough, 1979; Fordjor and others, 1983), Gulf of Alaska (Hottman and others, 1979), western Colorado, eastern Texas, and northern Canada (Gough and Bell, 1981, 1982), Auburn, N.Y. (Hickman and others, 1985; Plumb, 1982; Plumb and Hickman, 1985; Teufel, 1985), the Nevada Test Site (Healy and others, 1984; Springer and others, 1984), South Carolina (Zoback and others, 1985), and northern Germany (Blumling and others, 1983). In addition, stress studies of breakout development under laboratory conditions have been conducted on sandstone (Mastin, 1984), limestone (Haimson and Herrick, 1985), and coal (Kaiser and others, 1985) samples. The results of laboratory studies confirm the field observations of breakout development and offer detailed information on breakout formation under controlled conditions.

Breakouts, which are elongations in the cross sectional shape of near-vertical boreholes, were initially attributed to structural weakness of the wall due to steeply dipping fracturing and jointing (Babcock, 1978; Brown, 1978). Although Babcock (1978) concluded that natural fractures and jointing encountered during drilling affected the development of breakouts, he did speculate on the "unlikely" possibility that breakout development might be controlled by the existing stress field. Bell and Gough (1979) and Gough and Bell (1981) suggested that the existence of breakouts and the orientation of their development result from localized shear fracturing induced by large, unequal horizontal stresses concentrated at the well bore. They stated that the borehole will effect large changes in horizontal stresses near the well bore within hours of drilling and that this stress difference is resolved by shear fracturing of the wall. Numerous test cases comparing the orientation of breakouts and in situ stress directions inferred from other data indicate that breakouts will develop parallel to the direction of S_h (Bell and Gough, 1979, 1982; Gough and Bell, 1982; Zoback, 1982; Fordjor and others, 1983; Plumb and Hickman, 1985; Tuefel, 1985; Zoback and others, 1985).

Zoback and others (1985) observed in a study using borehole televiewer data that breakouts result from shear failure of the wall (fig. 1) where the concentration of compressive stress about the well bore is greatest. Mastin (1984) observed in laboratory stress experiments on circular holes in sandstone blocks that breakouts formed as a result of shear failure and extensional cracks oriented parallel to the wall in the direction of maximum horizontal stress (S_H). He found that the significance of either shear or extensional fracturing in the development of breakouts can vary with rock type and stress conditions and that the failure sequence governs breakout size and shape. Babcock (1978) observed that siltstone, sandstone, limestone, and dolomite generally yield breakouts with good cross sectional, ellipitical development, whereas breakouts occurring in shales tend to exhibit excessive hole enlargement or wall caving. Bell and Gough (1982) found that drilling fluid and mud pressures do not affect the orientation of breakouts, but they may contribute to or inhibit breakout development (Hottman and others, 1979). In a detailed cross section of the well bore using ultrasonic televiewer data, Zoback and others (1985) observed breakouts as "relatively broad, flat, curvilinear surfaces which enlarge the borehole." They concluded that well-bore diameter, cohesive strength of the rock, and relative magnitudes of horizontal stresses all influence the occurrence and extent of breakout development.

Currently, there is some discussion in the literature on the role rock discontinuities may play in the development and orientation of breakouts within the well bore. In laboratory studies of coal samples, Kaiser and others (1985) determined that the rupture sequence is not solely related to the orientation of principal stresses. They agreed with Babcock (1978) that the distribution of natural fractures influence the orientation of breakout formation. Also, in a study of well-bore elongations in a test well at the Nevada Test Site, Springer and others (1984) were able to associate breakout occurrence and direction with intense jointing. However, from field studies of borehole breakouts, Hickman and others (1985), Plumb and Hickman (1985), and Teufel (1985) concluded that the orientation and occurrence of breakouts was independent of natural fracture orientation. Although the degree of influence of rock discontinuities on breakout development is debatable, it is interesting to note, however, that Kaiser and others (1985) observed the

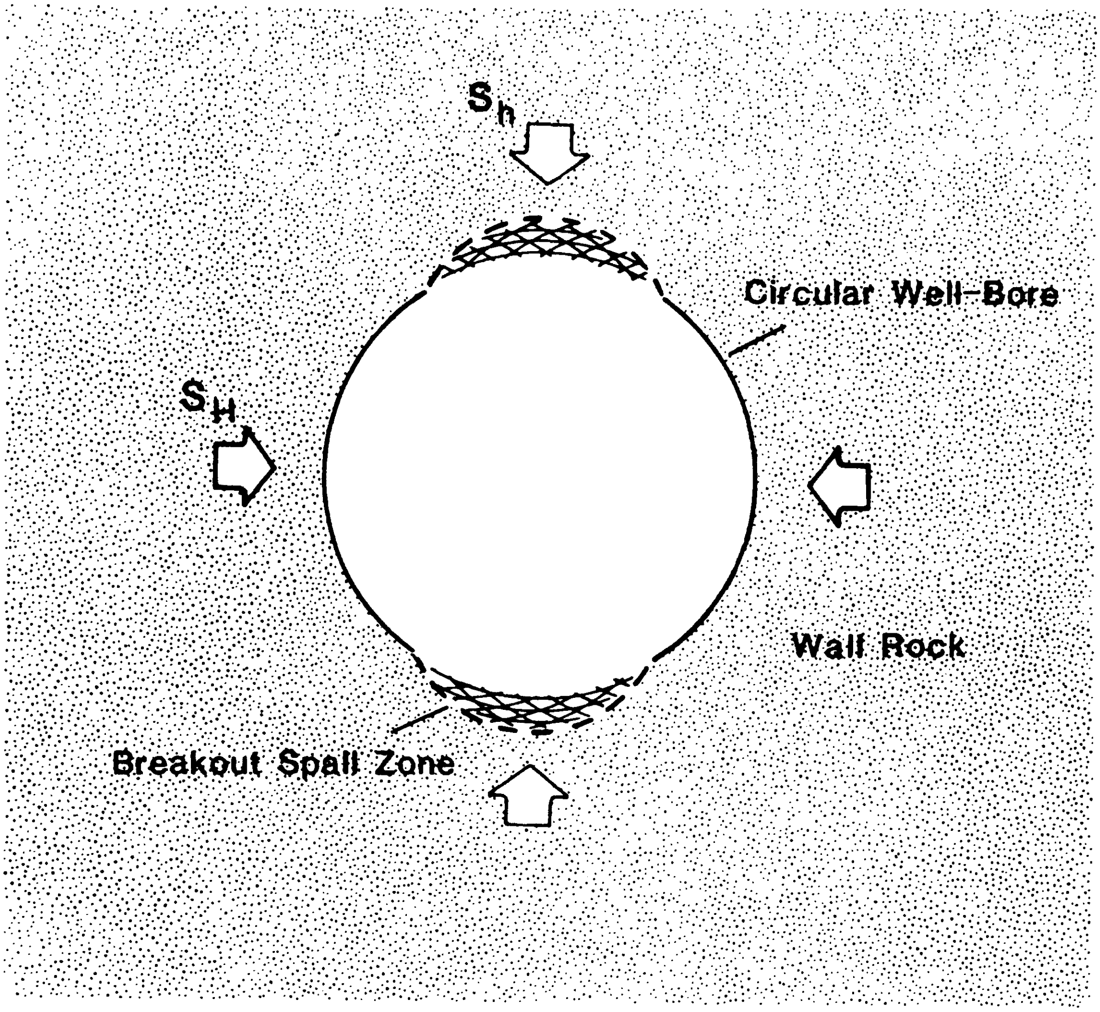

FIGURE 1.--A cross sectional schematic drawing of breakout. Breakout is oriented parallel to S_h. S_H and S_h are assumed to be horizontal and perpendicular to the vertical well-bore axis. Crisscross pattern within the breakout spall zone infers wall failure by extensional cracking (Mastin, 1984) and (or) shear fracturing (Zoback and others, 1985). Drawing is based on an original photo (Springer and others, 1984).

direction of jointing in their samples to be normal to the orientation of symmetric breakout rupturing, which they conclude to be related to the jointing. Whereas Hickman and others (1985) and Teufel (1985) draw the opposite conclusion about the relationship of breakout formation and natural fractural orientation, it is clear from their studies that steeply dipping natural fractures were also observed perpendicular to the direction of breakouts. There also appears to be a possible correlation between what Kaiser and others (1985) call "non-symmetric rupturing," which they observed when sample discontinuities were irregular, and what Plumb and Hickman (1985) refer to as "asymmetric borehole elongations", attributed to drill pipe wear. Both terms refer to borehole spalling on one side of the well bore and may in fact be the same thing.

The present study is an application of the breakout stress-orientation technique as described by Babcock (1978) and Gough and Bell (1982). The intent of this work is to gain additional information about the orientation of the regional stress field in the Denver and Illinois Basins. Agreement among stress directions inferred from breakout orientations in both basin study areas and other stress data, focal mechanism studies and in situ hydrofracture measurements (Zoback and Zoback, 1980; Logan, 1983), strongly suggests that breakout as well as hydrofracture orientations reflect the modern in situ stress field. A similar conclusion was reached by Bell and Gough (1982) from their observations of well-bore breakouts and hydraulically induced fractures in west-central Alberta.

WELL LOGS AND BREAKOUT DATA

Breakout orientations were determined from dipmeter and fracture-identification field logs from the Denver and Illinois Basins. The fracture-identification log, a special analysis of the four microresistivity curves recorded by the dipmeter tool, is designed to locate mud-filled vertical fractures (Schlumberger Limited, 1981). The high-resolution dipmeter logging tool (HDT) has four caliper arms positioned at 90° to one another and are fitted with one or more electrical conductivity pads (Schlumberger Limited, 1981). The HDT measures hole diameter, caliper orientation with respect to magnetic north, deviation of the borehole from vertical, and relative bearing of hole drift (Schlumberger Limited, 1981). For the purposes of detecting breakouts, the curve indicating azimuth of the No. 1 reference electrode is critical. Length of the breakout interval, amount of hole deviation from vertical, and azimuth of hole drift were recorded in addition to orientation of breakout.

Torque in standard logging cables results in a clockwise rotation of the tool under normal operating conditions (Schlumberger Limited, 1981). A breakout or zone of breakouts may temporarily interupt tool rotation. Borehole diameter conforms to bit size except when breakouts are encountered, or when hole diameter is enlarged (washed out) during drilling, or constricted because of mud caking (Babcock, 1978). Ideally, when a measureable breakout is encountered, two of the four paired caliper pads will expand and lock into the spalled depressions on opposite sides of the well bore and remain locked until the breakout terminates. The other two arms should maintain a constant spacing at the normal borehole diameter (bit size). During this interval, rotation may stop, slow down, or reverse (Babcock, 1978). However, very narrow or short breakouts may have no effect on normal tool rotation. Babcock (1978) suggests that in order to distinguish a breakout as a "unique event" the spacing difference of caliper pairs must be approximately 1/2 in. (1.28 cm) and that the minimum detectable length of breakout elongation is 2 ft (1.64 m). Bell and Gough (1982) state that if breakout width does not exceed caliper pad width, the breakout may go undetected. Pad width is 2.27 in. (5.85 cm) on the Schlumberger HDT-E and F tools (Bell and Gough, 1982). Examples of actual breakouts on well logs and an explanation of the procedure used to determine breakout orientation are given in Appendix A.

The basic criteria used in distinguishing breakouts from other forms of well-bore enlargement and nonsymmetrical caving are:

1. The logging tool must exhibit normal rotation at the start of the logging run.

2. One of the caliper pairs must exceed the borehole diameter relative to the bit size.

3. Normal tool rotation is interrupted.

4. Borehole elongations are not recorded as breakouts when (1) the direction of elongation and azimuth of hole drift coincide, and (2) there is a vertical deviation of the hole. Nonverticality of the well bore may induce drill-pipe wear in the form of asymmetric borehole elongation (Plumb and Hickman, 1985).

DENVER BASIN

The Denver Basin study area covers approximately 11,236 square miles (29,101 square kilometers) in the west-central part of the Denver Basin. The present-day Denver Basin (fig. 2) is an asymmetrical Laramide syncline trending north-south, paralleling the east flank of the Rocky Mountain Front Range uplift (Anderman and Ackman, 1963; Matuszcack, 1972). The unconformal base of Pennsylvanian age rocks defines the structural contour of the basin (Anderman and Ackman, 1963) (figs. 2, 3). The study area is located along the synclinal axis of the basin. Between the Front Range uplift and the deepest part of the basin in the vicinity of Denver, there is approximately 21,500 ft (6,555 m) of structural relief that includes approximately 12,000 ft (3,659 m) sediments ranging in age from Cenozoic to Paleozoic (Anderman and Ackman, 1963; Lindvall 1966). During drilling of the Rocky Mountain Arsenal well, northeast of Denver, Colorado (figs. 2, 3), crystalline basement rocks underlying the Denver Basin were encountered at a depth of 11,933 ft (3,638 m) (Healy and others, 1968). Formations comprising the Denver Basin sedimentary sequence accumulated during periods of Paleozoic uplift and subsidence. Maximum Paleozoic uplift of the ancestral Front Range highland was accompanied by maximum Paleozoic basin subsidence of the ancestral Denver Basin in Pennsylvanian time (Anderman and Ackman, 1963). Significant tectonic activity did not resume until Late Cretaceous time with Front Range uplifting and basin subsidence. The Front Range and the Denver Basin achieved their present-day structural configurations in the Eocene at the height of Laramide tectonism.

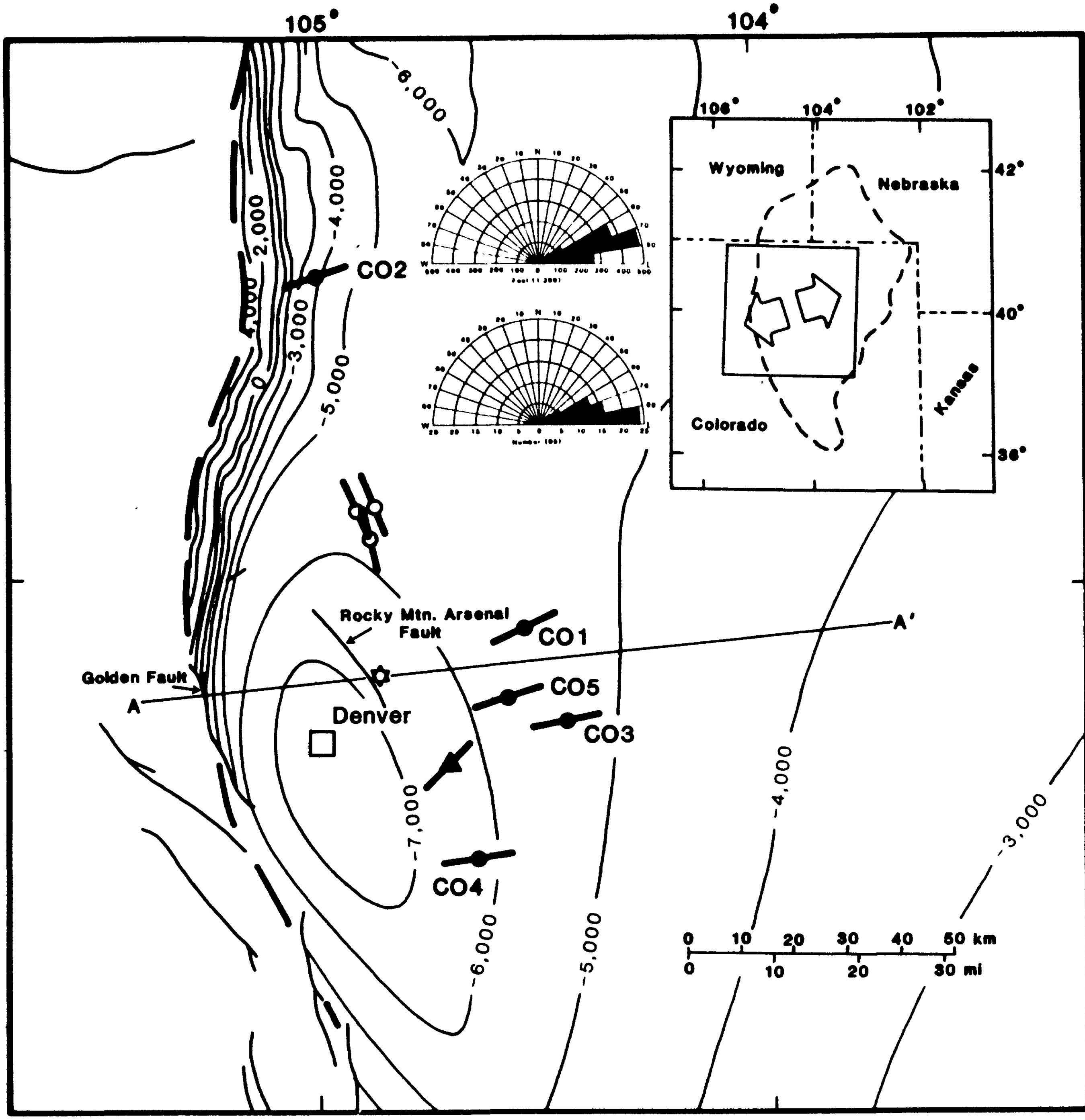

FIGURE 2.--Location of Denver Basin wells. ▬▬, basin boundary (Petroleum Information Corp., 1983). ——, study area shown on insert map. ⇨ (insert map), orientation of least horizontal compression inferred from breakout azimuths (see table 2). As illustrated, least horizontal compression is a function of feet of breakout for the basin. ⦿, well locations and mean orientation of breakouts from feet of breakout (see table 1). ○, well locations and hydraulic fracture orientations (Logan, 1983). ⬋, average epicentral location of several earthquake local mechanisms associated with Rocky Mountain Arsenal injection well, and approximate orientation of S_h (Zoback and Zoback, 1980). ✡, marks the approximate site of the Rocky Mountain Arsenal well (Evans 1966). Inserts of composite rose diagrams of basin breakout orientations are of feet and number of breakouts. ⋌, locations of Cenozoic faulting (Kirkham and Rodgers, 1981). Basin contour interval is 1,000 ft; datum is mean sea level. Contours indicate top of Mississippian rocks or older rocks where Mississippian is absent (Anderman and Ackman, 1963).

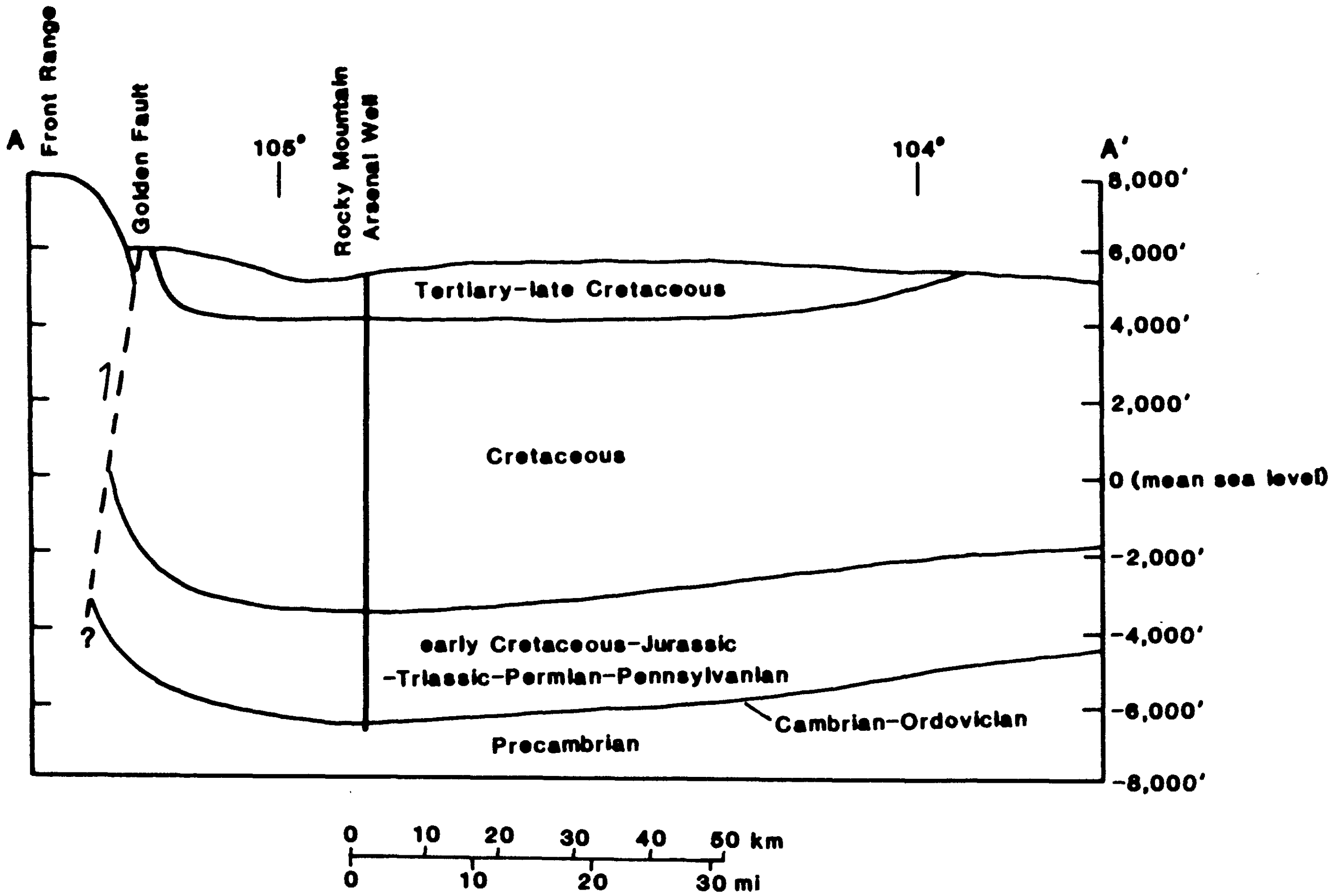

FIGURE 3.--Denver Basin cross section, A-A (modified from Evans, 1966; Lindvall, 1966). Depth is in feet. (See table A-1.)

The Front Range west and south of Denver is bounded by a number of southeast-trending high-angle reverse, thrust, and normal faults (Anderman and Ackman, 1963; Zoback and Zoback, 1980; Kirkham and Rodgers, 1981) (fig. 2). These faults cut into Denver Basin sediments. Although these Cenozoic faults are considered potentially active they, with the exception of the Rocky Mountain Arsenal fault, appear to be aseismic at the present time (Kirkham and Rodgers, 1981). The Rocky Mountain Arsenal fault as delineated by the epicentral zone of earthquakes is believed to be a deep basement-controlled, nearly vertical normal fault or fracture zone that strikes approximately N. 45° W. and is estimated to be 16 km in length (fig. 2) (Zoback and Zoback, 1980; Kirkham and Rodgers, 1981). The epicentral zone lies in the Precambrian basement below the base of the arsenal well, and no significant faulting has been found in the overlying sedimentary rock (Lindvall, 1966; Hollister and Weimer, 1968).

The Denver Basin study area is located within the Southern Great Plains physiographic province. Zoback and Zoback (1980) determined a direction of least principal horizontal stress of north-northeast to south-southwest for the Southern Great Plains area as a whole. They observed that this area is controlled by a rather uniform state of stress and that basaltic volcanism in New Mexico and earthquake focal mechanisms in eastern Colorado indicate it to probably be an extensional-stress regime. This condition contrasts with the generally compressional tectonics of the rest of the mid-Continent area (Zoback and Zoback, 1980).

Cuttings and core samples from 11,933 ft (3,638 m) of nearly flat-lying sediments from the Rocky Mountain Arsenal well (Lindvall, 1966; Healy and others, 1968) constitute a general stratigraphic section for wells in the Denver Basin study area (table A-1; fig. 3). More detailed stratigraphic descriptions of the formations logged in the five wells used in this study were not available.

The following discussion of apparent correlations between breakout occurrence in Denver Basin wells and rock type is based on the structural contours of the base of the Denver Basin within the study area (figs. 2, 3) and on the detailed stratigraphy of the Rocky Mountain Arsenal well (table A-1). The greatest concentration of breakouts appears between -1,300 and -2,600 ft (-396 and -793 m) (fig. 4) near the base of the Cretaceous section (fig. 3). Breakouts from all five Denver Basin wells occur within this interval. The stratigraphy at this depth interval grades from Cretaceous shale interbedded with siltstone and sandstone, calcareous to chalky shale and limestone, to Early Cretaceous shaley limestone, micaceous shale, fine-grained sandstone, shale and hard-quartzitic sandstone (Lindvall, 1966). Data from well C02 span the greatest lithologic interval, more than 4,000 ft (1,220 m), from Tertiary and Late Cretaceous sandstone and shale to Early Cretaceous shale and limestone (figs. 3, 4). Exact correlation of breakout occurrence with specific rock types was not possible. Despite this limitation, it appears from the data available that breakouts developed throughout the sampling interval regardless of lithologic environment.

Rose diagrams of breakout orientations for individual wells (fig. 5) show a very consistent east north-east, south south-west to east-west pattern of breakout. This orientation of breakouts is best expressed in composite rose diagrams for the basin (insert on fig. 2). The orientation of S_h is inferred

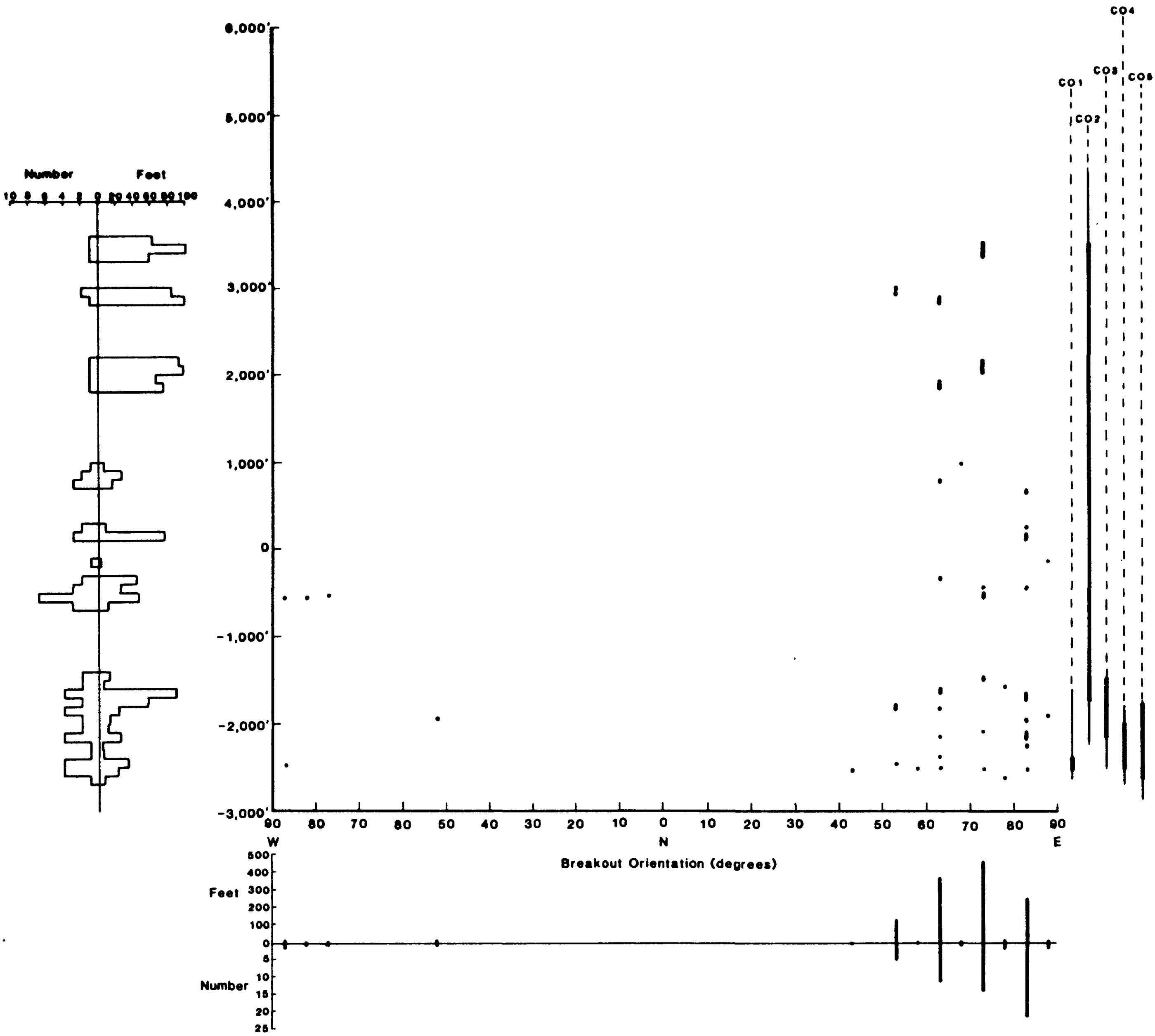

FIGURE 4.--Scatter diagram and frequency graphs of Denver Basin breakouts. Depth is measured in feet. Vertical bar graph (left) shows frequency of breakout occurrence (feet and number of breakouts) with depth. Horizontal bar graph indicates frequency of breakout occurence (feet and number of breakouts) with direction. Depth of drilling, interval of logging, and depth of breakout occurrence for each well are represented as dashed, thin-solid and thick-solid lines, respectively (see table A-12).

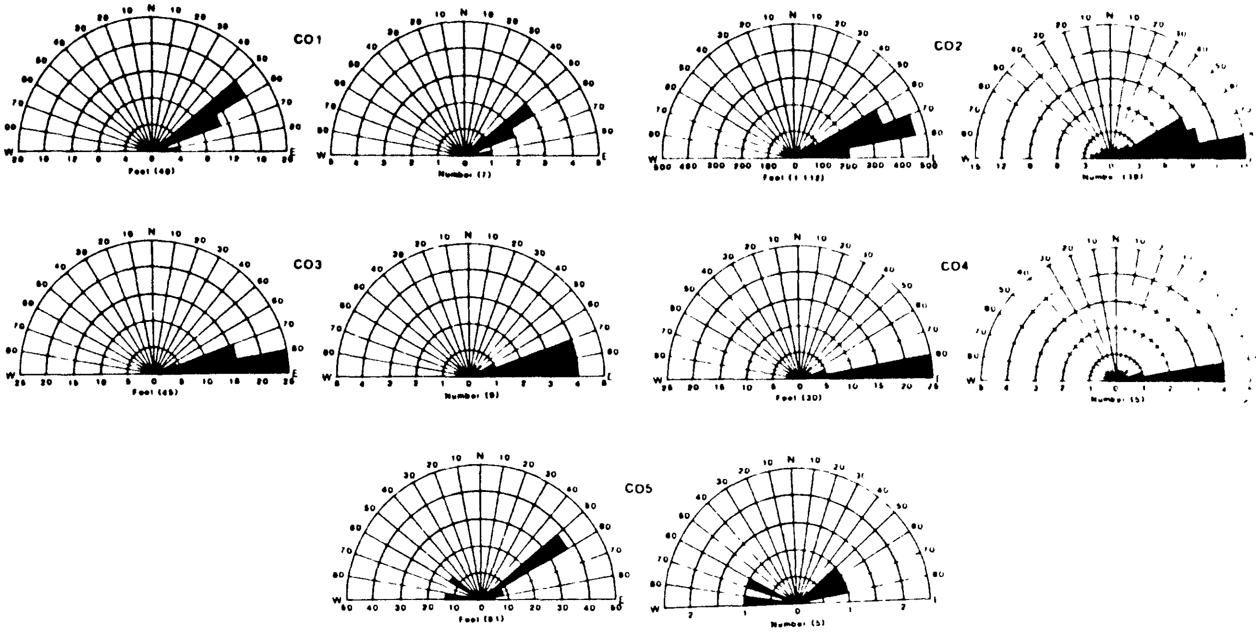

FIGURE 5.--Frequency rose diagrams of breakout orientations from Denver Basin wells. Feet and number (numbers in parentheses) refer to the totals of feet of breakout and the number of breakouts, respectively, for each well.

to be parallel to the mean direction of breakout. Other stress studies offer support for this observation. Focal mechanisms of earthquakes associated with the Rocky Mountain Arsenal fault indicated a mean S_h direction of approximately N. 45° E. (Zoback and Zoback, 1980). Induced hydraulic fractures from three wells in the Wattenburg field (fig. 2) north of Denver, Colo., indicated a mean S_H orientation of N. 18° W. (Logan, 1983). Although Logan concluded that induced tensional fractures are controlled to some extent by elements of rock fabric, he could not exclude the influence of in situ stress in their development. In situ stress-related borehole breakouts from Denver Basin wells formed at approximately right angles to the Wattenburg field hydraulic fractures.

ILLINOIS BASIN

The Illinois Basin is defined as the area enclosed by the top of the Ottawa Limestone megagroup of Middle Ordovician age (Bell and others, 1964; Willman and others, 1975) (figs. 6, 7). This study area is oriented north-northwest covering approximately 25,921 square miles (67,136 square kilometers), including all of southern Illinois and parts of Kentucky and Indiana. Within the study area, the Illinois Basin achieved its maximum depth near the intersection of Illinois, Kentucky, and Indiana. This central depression is known as the Fairfield Basin (Bell and others, 1964) and is roughly outlined by the 5,000-ft basin contour (fig. 6). The deepest part of the Illinois Basin is filled with 15,000 ft (4,573 m) of consolidated Paleozoic marine sediments (William and others, 1975). Basin subsidence probably began during the Cambrian and continued intermittently until the end of the Paleozoic (Willman and others, 1975). Accurate timing of periods of major tectonic movement in the Illinois Basin is prevented by lack of Permian, Triassic, Jurassic, and Lower Cretaceous rocks. However, deformation of Pennsylvanian rocks probably coincides with the Appalachian Revolution at the close of the Paleozoic Era (Willman and others, 1975).

The Illinois Basin study area is in a region referred to by Heyl and Brock (1961) as the Illinois-Kentucky mining district. They describe this area as being a collapsed, block-faulted, slipped and partly rotated domal anticline located at the junction of several major fault systems. This southeast-plunging domal anticline is the dominant structural feature within the study area. The Hicks dome centered near 37°30' W., 88°20' N. (fig. 6) forms the structural high point of the anticline. Heyl and Brock (1961) speculate that the Hicks dome and the anticlinal domal folding of Paleozoic basin sediments probably occurred in response to the injection of magma along deep-seated tensional fractures within the Precambrian basement. They concluded that doming occurred over a short period of time, most likely in Middle Cretaceous time, and that collapse and rotation occurred simultaneously as a result of cooling and shrinking of the intruded magma and compressive stress on east-west-trending fault zones, respectively. They did not speculate on the cause of initial, tensional basement fracturing.

The southern part of the Illinois Basin is located within a seismically active part of the broad Midcontinent province. Earthquake focal mechanism in this region indicates strike-slip and reverse faulting result from an approximately east-west compressive-stress field (Zoback and Zoback, 1980).

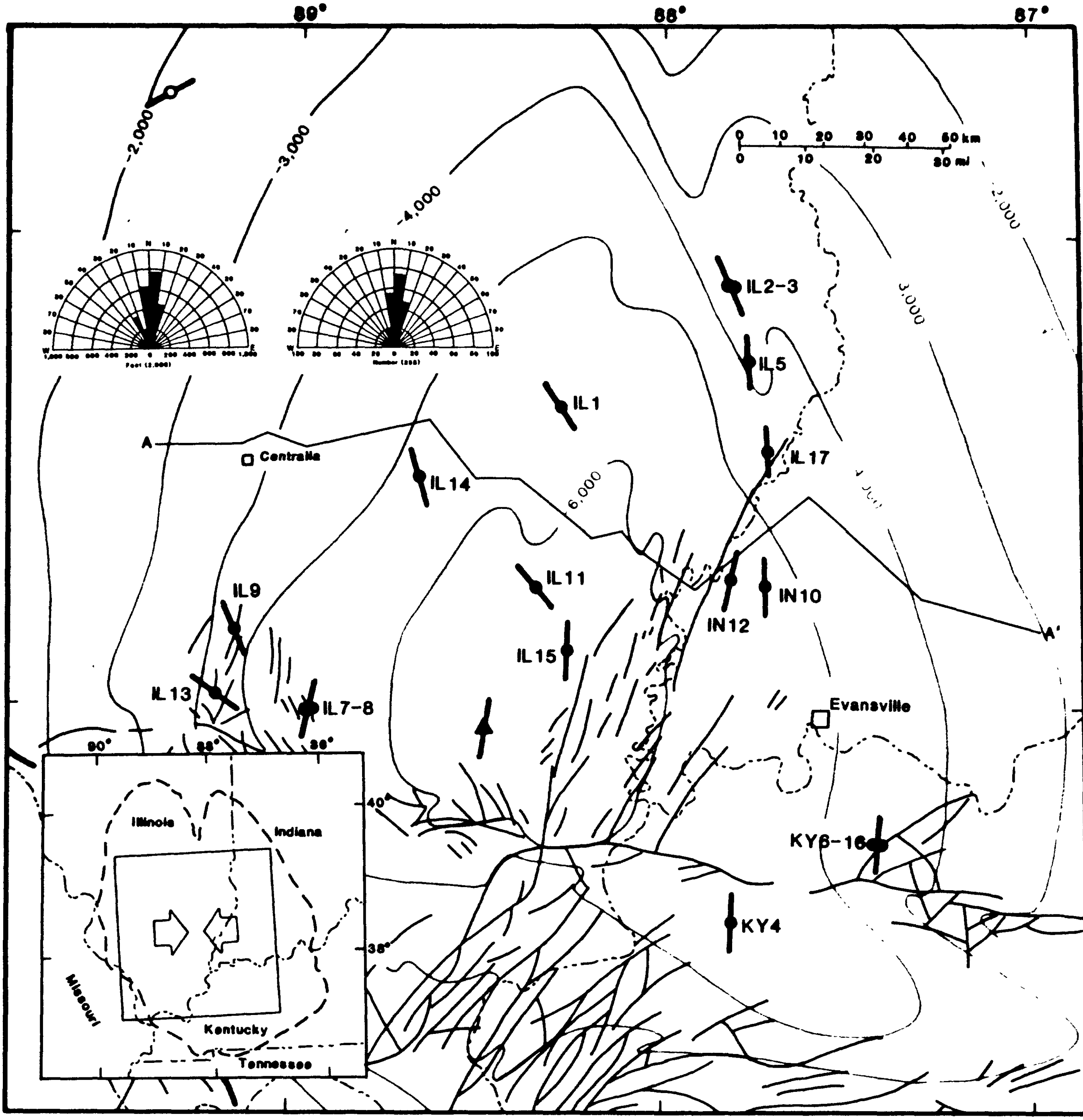

FIGURE 6.--Location of Illinois Basin wells. ▬ ▬, basin boundary (Bell and others, 1964). ——, study area on the insert map. ⇨ (insert map), orientation of maximum horizontal compression inferred from breakout azimuths (see table 2). As illustrated, maximum horizontal compression is a function of feet of breakout for the basin. ⦁, well locations and mean orientation of breakouts from feet of breakout (see table 1). ⦰, well location with orientation of hydraulic fractures (Zoback and Zoback, 1980). ▲, epicentral location and the orientation of S_h of a single-event earthquake focal mechanism (Zoback and Zoback, 1980). Inserts of composite rose diagrams of basin breakout orientations are feet and number of breakouts. ⟋, significant faulting (Heyl and Brock, 1961). IL, IN, and KY identify wells located in Illinois, Indiana, and Kentucky, respectively. Basin contour interval is 1,000 ft; datum is mean sea level. Contours indicate top of Ordovician, Ottawa Limestone (Bell and others, 1964).

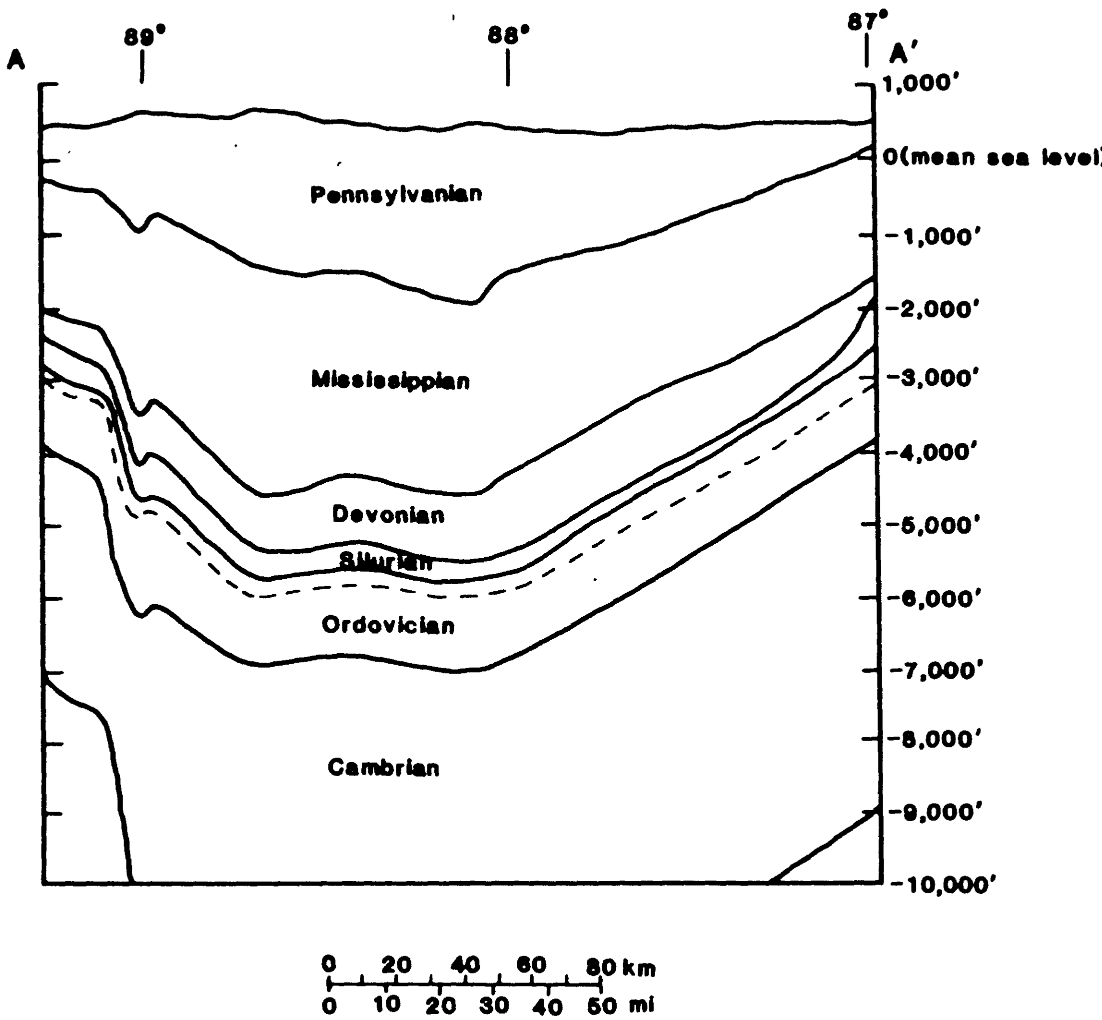

FIGURE 7.--Illinois Basin cross section, A-A', (modified from Bell and others, 1964). Depth is in feet. (See table A-2.) Dashed line marks the bottom of the basin (top of the Ottawa Limestone).

Because lithologic units dip steeply toward the deepest part of the Illinois Basin, vary in thickness laterally, and are highly faulted within the study area (fig. 6), accurate correlation between depths of breakout occurrence and rock composition and structure is questionable without detailed stratigraphic data for each well. However, very general correlations between lithology and breakout formation are possible. The vertical bar graph of breakout occurrence with depth (fig. 8) indicates breakout development at two levels: between -800 and -2,700 ft (-244 and -823 m) and between -4,000 and -5,000 ft (-1,220 and -1,524 m). Primary contributors to the shallower breakout zone are wells IL 1, 3, 7, 8, 14, and 17, KY 4, 6 and 16, and IN 10 and 12. Breakouts within this shallow zone occur in lower Pennsylvanian- and Mississippian-age rocks (fig. 7). The Pennsylvanian rocks are principally sandstone with minor amounts of siltstone and shale; Mississippian rocks are primarily limestone alternating with shale and sandstone (Willman and others, 1975). The second, deeper zone of breakouts appears to have developed in rocks ranging in age from lower Mississippian to possibly upper Ordovician (figs. 7, 8). This deeper zone is comprised of breakouts from wells IL 5, 9, and 11. Rock composition at this depth varies from Mississippian shale and siltstone; Devonian shale, limestone and dolomite; Silurian limestone, siltstone and shale to Orodovican dolomite (Willman and others, 1975). A slight northwest rotation, approximately 15°, in the mean orientations of breakouts within this deeper zone (fig. 8) does not appear to be related to rock type, but it may reflect a shift in the direction of horizontal stress with depth.

Composite rose diagrams for the Illinois Basin (insets fig. 6) show the consistency of breakout data; the preferred orientation is north-south. In figure 9, some variation in breakout direction among individual well data sets is indicated. As with the Denver Basin breakouts, in situ stress directions inferred from Illinois Basin breakout orientations are confirmed by other stress data. The P axis of a well-constrained, single-event focal mechanism located in southern Illinois was essentially horizontal and oriented N. 83° W., and a hydrofracture measurement from a well in south-central Illinois at a depth of 328 ft (100 m) (fig. 6) indicated an S_H orientation of N. 60° E. (Haimson, 1974; 1977).

DISCUSSION

Mean directions of breakout and values of mean angular deviation were computed from both the number of breakouts and feet of breakout for azimuths of breakout. These values were calculated for each individual well data set and collectively for all the wells in a basin. The breakouts in each data set (well or basin) were considered as an axially symmetric, circular-normal distribution of vectors in two dimensions. Vector direction and length are breakout azimuth and breakout frequency (either number of breakouts or feet of breakouts). Therefore, two values of mean direction and mean angular deviation were calculated for each well and basin data set (tables 1 and 2). The 95-percent confidence limits of the computed mean directions for the basins (table 2) are estimates of prediction accuracy. Mean angular deviation, like standard deviation, is a measure of dispersion of the data about the computed mean direction (Batschelet, 1965). In table 2, for example, the computed mean direction ($\bar{\theta}$) for number of breakouts for Denver Basin wells is 76±3° and the mean angular deviation (A) is 13°, that is to

TABLE 1.--Mean breakout directions: wells

[Mean directions of breakout ($\bar{\theta}$) and angular deviation (A). Calculations are based on cumulative feet of breakout and number of breakouts for directions of breakout in each well]

Well No.	Calculations in degrees			
	Number		Feet	
	$\bar{\theta}$	A	$\bar{\theta}$	A
Denver Basin				
CO1	N. 59 E.	11	N. 64 E.	13
CO2	N. 76 E.	11	N. 71 E.	9
CO3	N. 78 E.	7	N. 78 E.	7
CO4	N. 81 E.	4	N. 81 E.	4
CO5	N. 80 E.	24	N. 72 E.	26
Illinois Basin				
IL1	N. 34 W.	13	N. 33 W.	8
IL2-3	N. 18 W.	16	N. 25 W.	13
KY4	N. 1 W.	10	N. 2 E.	9
IL5	N. 1 W.	18	N. 4 W.	18
KY6-18	N. 4 E.	10	N. 3 E.	9
IL7-8	N. 9 E.	14	N. 12 E.	16
IL9	N. 18 W.	13	N. 23 W.	10
IN10	N. 5 W.	9	N. 2 W.	7
IL11	N. 40 W.	12	N. 40 W.	12
IN12	N. 11 E.	7	N. 9 E.	6
IL13	N. 61 W.	14	N. 55 W.	10
IL14	N. 17 W.	8	N. 16 W.	9
IL15	N. 9 W.	31	N. 0	26
IL17	N. 2 W.	19	N. 4 W.	20

TABLE 2.--Mean breakout directions: basins

[Mean directions of breakout ($\bar{\theta}$) and angular deviation (A). Predicted variations in mean directions (±) are the 95-percent confidence invervals. Calculations are based on cumulative feet of breakout and number of breakouts for azimuth of breakout in each basin]

Basin	Calculations in degrees			
	Number		Feet	
	$\bar{\theta}$	A	$\bar{\theta}$	A
Denver----	N. 76 E.±3.0	13	N. 73 E.±0.6	10
Illinois--	N. 0 ±2.2	18	N. 2 W.±0.7	19

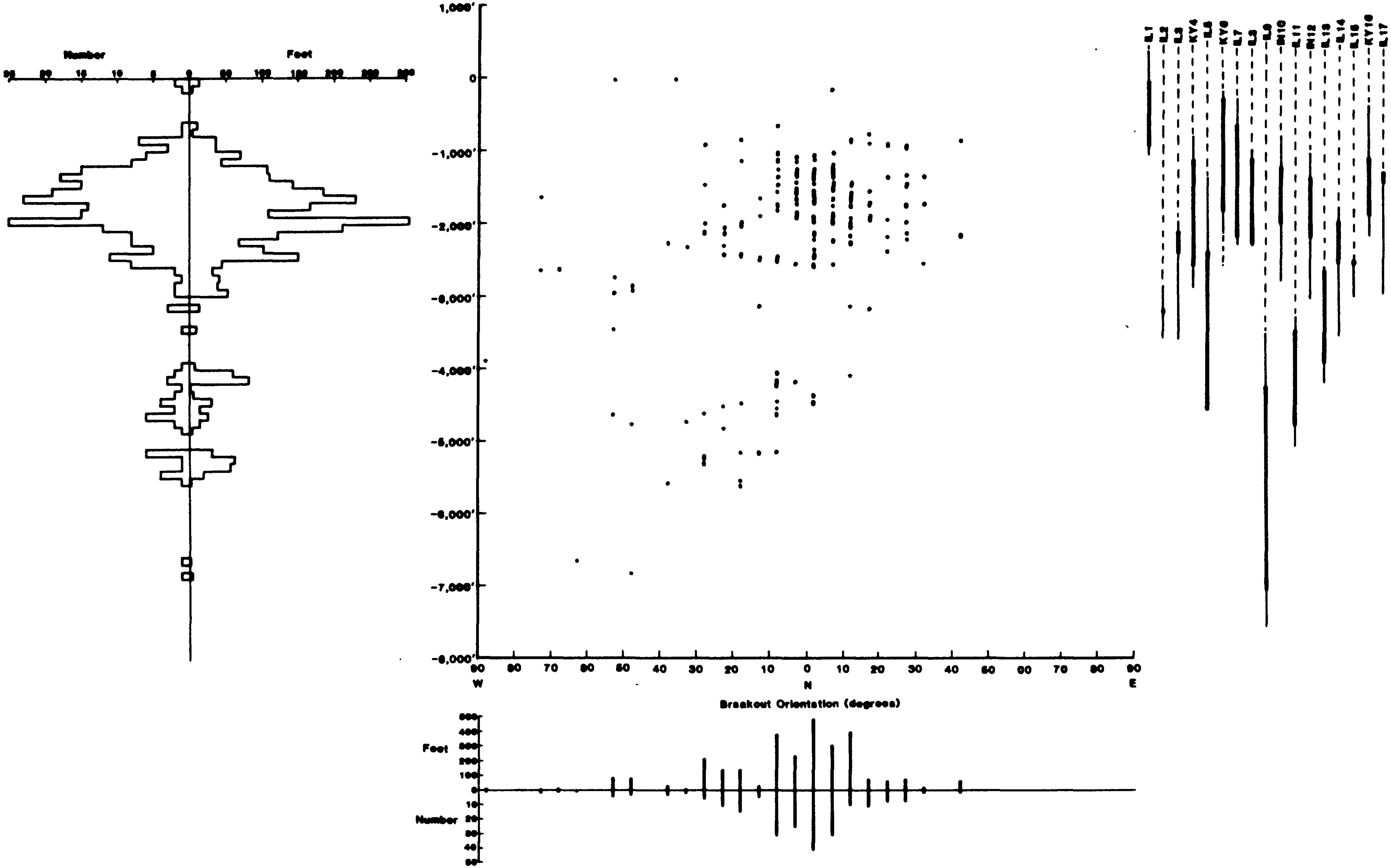

FIGURE 8.--Scatter diagram and frequency graphs of Illinois Basin breakouts. Depth is measured in feet. Vertical bar-graph (left) shows frequency of breakout occurrence (feet and number of breakouts) with depth. Horizontal bar-graph indicates frequency of breakout occurrence (feet and number of breakouts) with direction. Depth of drilling, interval of logging and depth of breakout occurrence for each well are represented as dashed, thin-solid and thick-solid lines, respectively (see table A-12).

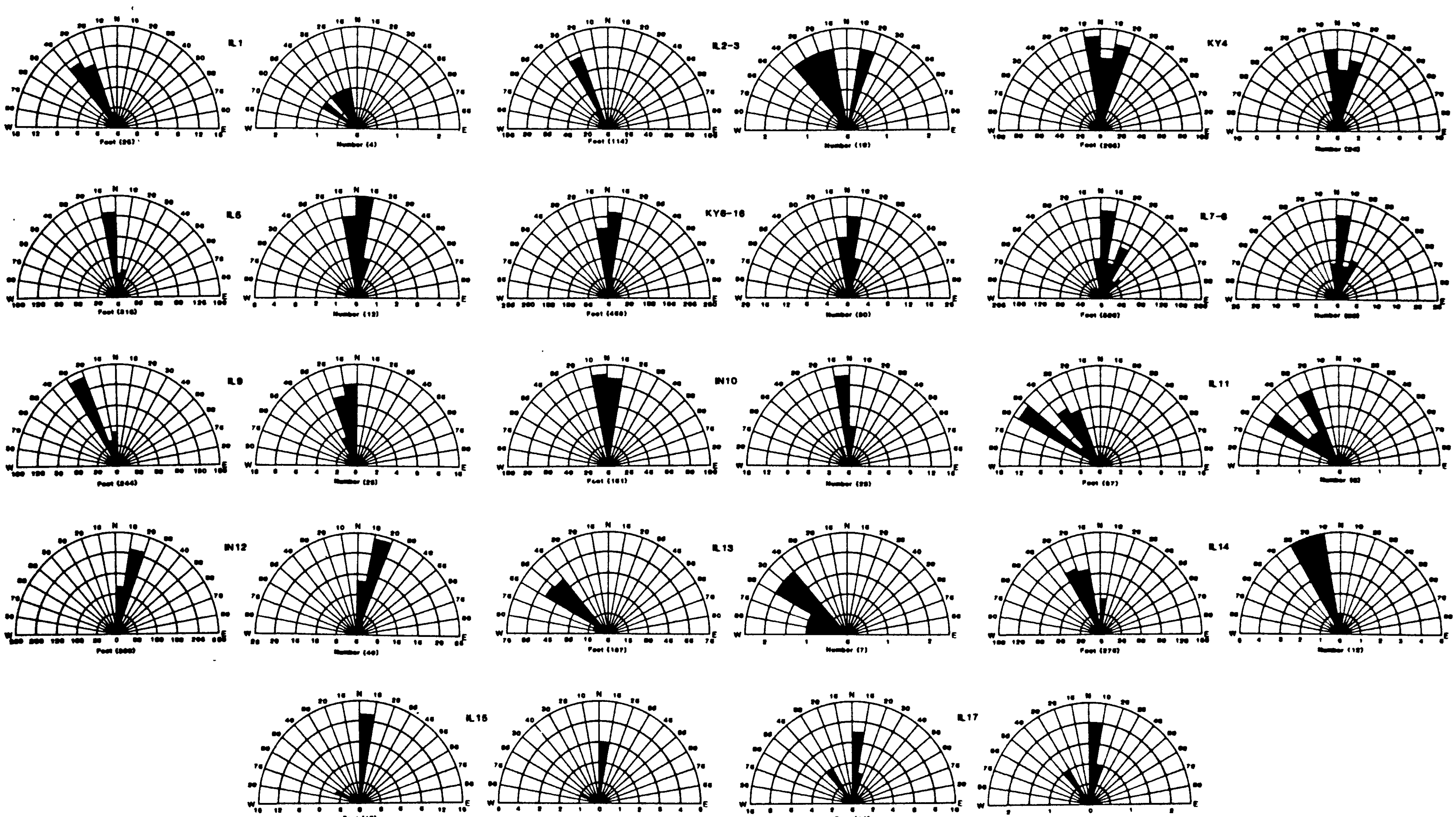

Figure 9.--Frequency rose diagrams of breakout orientations from Illinois Basin wells. Feet and number (numbers in parentheses) refer to the totals of feet of breakout and the total number of breakouts, respectively, for each well.

say, the true value of the mean direction is within ±3° of 76° and that 67 percent of the data had orientations within 13° of the predicted mean direction.

Breakout vectors within a data set were treated either individually or were grouped in degree intervals. Vector frequencies of basin data sets were grouped in 10° intervals (see tables A-6 and A-10). The method used in the calculation of circular mean direction and angular deviation is detailed in Appendix 2.

Tables 1 and 2 list the computed mean direction of breakout and angular deviation for each well and basin data set. Directions of S_h are inferred for each data set from mean breakout orientations ($\bar{\theta}$). Values of $\bar{\theta}$ for both feet or breakout and number of breakouts are very similar for individual well breakouts as well as basin breakouts. Differences between the mean values of $\bar{\theta}$ of only 3° and 2° were found for the Denver and Illinois Basins, respectively. This excellent agreement indicates a high degree of consistency among breakout orientations within the two basin data sets.

Breakouts in the Illinois Basin appear to form at different depths with slightly different orientations. Most of the breakouts from -1,000 to -3,000 ft are oriented between N. 12° E. and N. 8° W. But between the 4,000- and 5,500-ft depth, they have a more northwesterly orientation of N. 8° to 28° W. indicating an apparent counterclockwise change in S_h orientation with depth.

Among the five Denver Basin wells used in this study, 65 breakouts consisting of 1,308 ft of breakout were measured (tables A-4 and A-5). For the purpose of computing mean breakout direction and angular deviation for the basin, measured azimuths were grouped into 10° intervals (table A-6). From the 17 Illinois Basin wells studied, a total of 2,904 ft of breakout in 257 breakouts were measured (tables A-8 and A-9). As with the Denver Basin breakouts, the Illinois Basin azimuths of breakout were also grouped into 10° intervals (table A-10).

CONCLUSIONS

Scatter in breakout orientation from the computed mean direction of breakout for each basin can be attributed in part to reader error, tool miscalibration, and drill-pipe wear or possibly rock discontinuities (natural fracture, rock fabric, or rock heterogeneities). Because of the relatively good consistency among breakout directions in a wide range of rock types, the possible influence of rock discontinuities on breakout orientation appears to be of minor importance. A similar conclusion was made by Babcock (1978).

Breakout data from the Denver and Illinois Basins infer reliable estimates of S_h orientations in these two ares because (1) breakout orientations were consistent within individual wells, (2) breakout orientations consistent within each basin, and (3) there was agreement between breakout orientations and other stress data. Breakout orientations imply mean S_h directions at the 0.95 confidence level of N. 73°±0.6° to 76°±3.0° E. along the eastern flank of the Front Range in central Colorado (west-central Denver Basin) and N. 0°±2.2° to N. 2°±0.7° W. in southern Illinois, southern Indiana, and western Kentucky (south-central Illinois Basin). The Denver Basin is probably being subjected to regional extensional tectonics (Zoback and Zoback, 1980). In light of this and the mean orientation of breakouts from Denver Basin wells, the direction of minimum horizontal compression for the study area is inferred to be generally east-northeast to west-southwest. In contrast, the direction of maximum horizontal compression as determined from the overall north-south orientation of Illinois Basin well breakouts is approximately east-west. This finding is in agreement with the general northeast to east-west regional direction of maximum principal horizontal compression for the Midcontinent region (Zoback and Zoback, 1980).

As a result of the apparent consistency between breakout orientations and other stress data, hydrofracture measurements and earthquake focal mechanisms, and the relatively low cost and availability of well logs, the breakout technique, as used in this and other studies, can be a useful indicator of regional stress orientation.

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APPENDIX A

EXAMPLES OF BREAKOUTS ON DIPMETER AND FRACTURE IDENTIFICATION WELL LOGS

Paired caliper separations on figure A-1 indicate a number of breakouts on that section of the dipmeter log. Breakouts can be seen at -2,432 to -2,439; -2,371 to -2,377; and -2,170 to -2,206 ft. Normal tool rotation is indicated by the diagonal trace of the No. 1 reference electrode below -2,440 ft. At -2,440 ft, normal rotation is interrupted and the reference electrode curve becomes vertical. Between -2,432 and -2,439 ft, calipers 2-4 are locked in the breakout elongation. The azimuth of the reference electrode can be measured directly off the log record using the 0° to 360° scale. Because this breakout is tracked by the 2-4 calipers, its direction is found by adding the magnetic declination (east declinantion) of the well location to the azimuth of the No. 1 reference electrode, which corresponds to the 1-3 calipers, and subtracting 90°. In this case, the azimuth of the No. 1 electrode is 170°. By adding to this value the magnetic declination of 2° and subtracting 90°, the direction of the breakout is N. 82° E. The vertical deviation at this depth is approximately 0.25°, and the azimuth of hole drift is 80°. Although the orientation of the breakout is essentially the same as the azimuth of hole drift, the vertical deviation is so small that this borehole elongation is probably stress-induced. The abrupt terminations of the breakout also suggest that they are not a result of vertical deviation. Breakouts can also be seen on the fracture identification log (fig. A-2) at depths of -2,705 to -2,720, and -2,534 to -2,590 ft. A vertical-deviation curve was not included on this log (fig. 2); therefore, it is impossible to determine the amount of vertical deviation for any of these breakouts. In this example of a fracture identification log, separation in the overlapped resistivity traces, which would indicate vertical wall fractures, is not indicated. The presence of permeable beds is evidenced by the high-frequency left-shifting of all four resistivity traces at various levels.

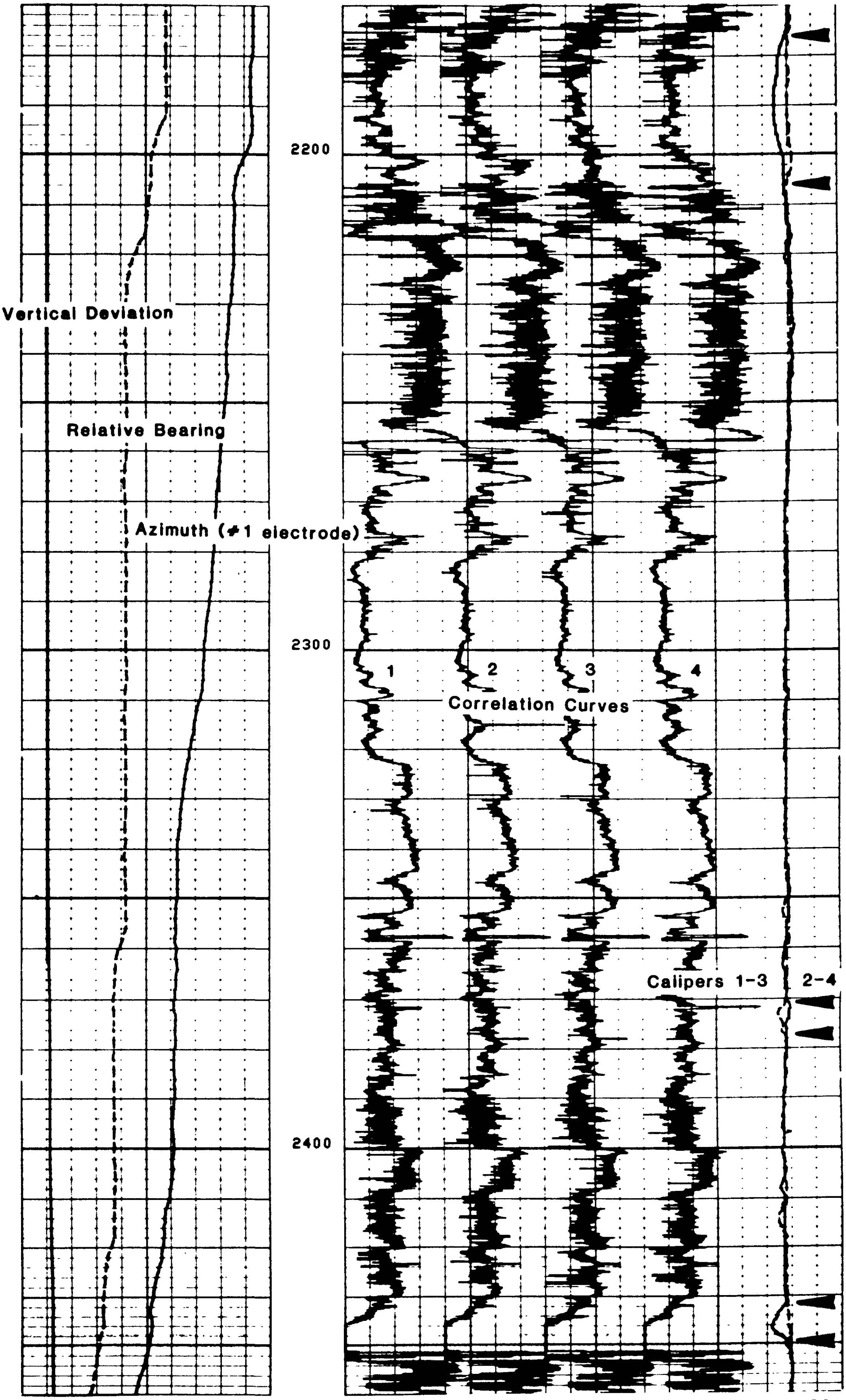


FIGURE A-1.--Part of the dipmeter-log record from Illinois Basin well IN10. Arrows indicate limits of individual breakouts.

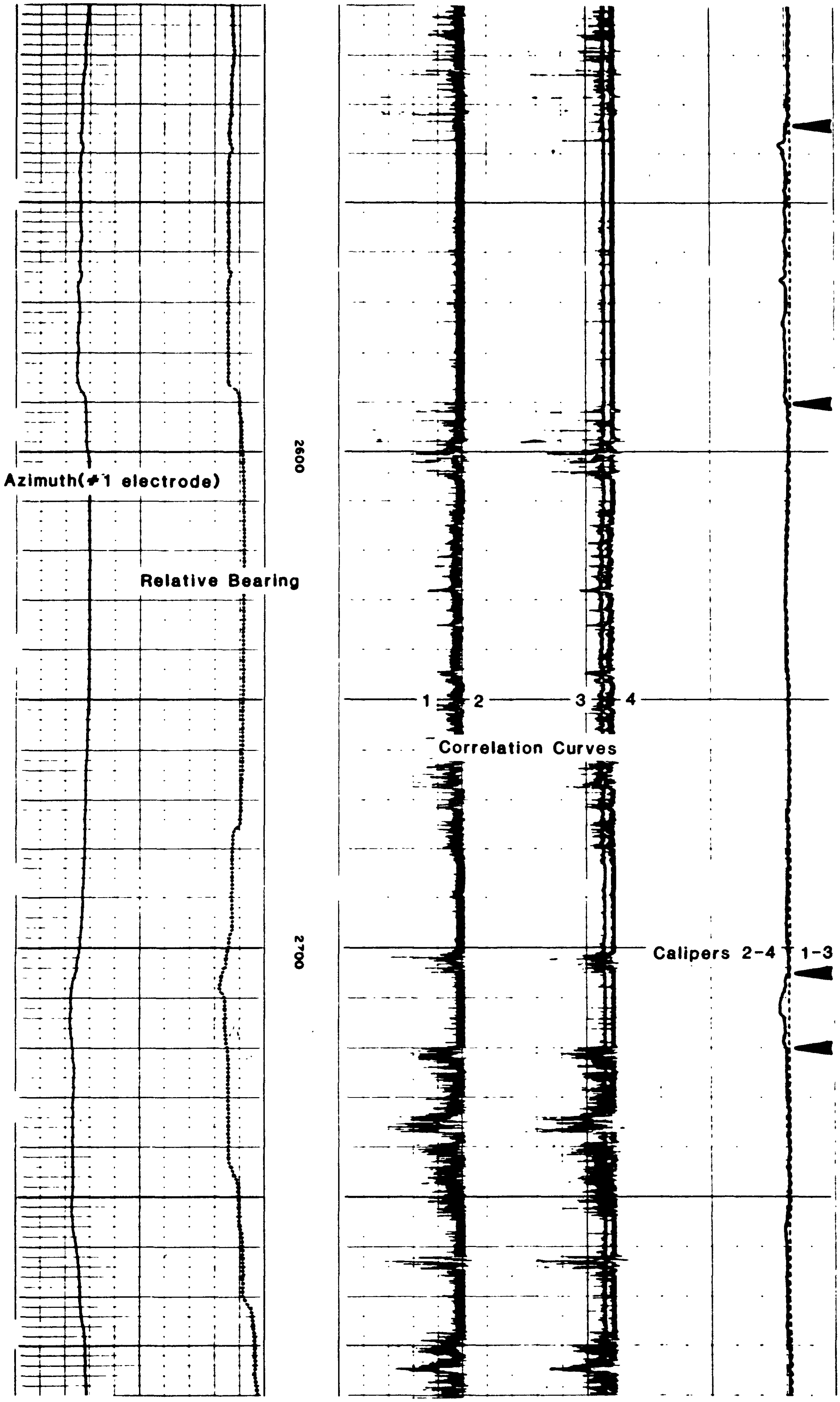


FIGURE A-2.--Part of fracture-identification-log record from Illinois Basin well IL3. Arrows indicate limits of individual breakouts.

TABLE A-1.--Denver Basin stratigraphy

[Generalized basin stratigraphy in the vicinity of Denver, Colo., from Rocky Mountain Arsenal well data. Information in this table is from Lindvall, (1966)]

Formation age	Depth (feet)		Lithology
	From	To	
Quarternary----------------	5,200	5,170	Unconsolidated dune sand, sand, silt, and gravel.
Late Cretaceous------------	5,170	4,740	Shale, siltstone, sandstone and conglomerate.
Do---------------------	4,740	3,950	Alternating fine-grained sandstone, shale, and coal beds.
Do---------------------	3,950	3,720	Fine-grained sandstone with shale interbedding.
Do---------------------	3,720	-2,510	Shale interbedded with siltstone and sandstone.
Early and Late Cretaceous--	-2,510	-2,878	Calcareous to chalky shale and limestone.
Do---------------------	-2,878	-3,285	Shaly limestone to micaceous shale.
Early Cretaceous-----------	-3,285	-3,586	Grades from quartzitic sandstone to sandstone and shale to hard quartzitic sandstone.
Jurassic-------------------	-3,586	-3,772	Shale with thin beds of limestone, hard sandstone, and anhydrite.
Triassic-------------------	-3,772	-4,382	Fine-grained, hard, quartzitic sandstone (15 ft), anhydrite, and shale (80 ft).
Permian--------------------	-4,382	-4,572	Fine-grained, highly fractured, quartzitic sandstone.

TABLE A-1.--Denver Basin stratigraphy--Continued

Formation age	Depth (feet)		Lithology
	From	To	
Pennsylvanian and Permian--	-4,572	-6,680	Coarse-grained arkosic conglomerate, siltstone, shale, and thin limestone beds. Upper third is highly fractured.
Fossil soil----------------	-6,680	-6,695	Weathered shale.
Ordovician or Cambrian-----	-6,695	-6,750	Quartz conglomerate, shale, coarsely crystalline dolomite with chert fragments.
Precambrian----------------	-6,750	-6,770	Weathered schist.
Do--------------------	-6,770	-6,845	Highly fractured (vertical) granite with pegmatite intrusions.

TABLE A-2.--Illinois Basin stratigraphy

[Generalized basin stratigraphy in the vicinity of the study area from well data. Rock-unit ages and lithologic descriptions are from Willman and others (1975). See cross section (fig. 7) for relative depths of rock units]

Formation age	Lithology
Pleistocene or Paleozoic	Varies locally (glacial drift, lake deposits, and consolidated bedrock).
Pennsylvanian	Clastic rocks, principally sandstone with siltstone, shale, and small amounts of coal and limestone.
Mississippian	Limestone with some siltstone, shale, and sandstone formations.
Devonian	Varies vertically from siliceous limestone, dolomite, and chert to pure limestone to shale with some limestone and siltstone.
Silurian	Limestone, siltstone and shale in southern Illinois.
Ordovician	Dolomitized limestone with some sandstone and shale formations.
Cambrian	Medium-grained sandstone.

TABLE A-3.--Denver Basin wells

[Unit, low- or high-angle dipmeter tool used; DEV and AHD, approximate average values of vertical deviation and azimuth of hole drift, respectively. Log refers to either dipmeter (DIP) or fracture identification (FIL)]

Well	Location			Unit	DEV (degrees)	AHD (degrees)	Log
	Sec.	T.	R.				
C01	27	1 S.	64 W.	Low	1	N. 20-80 E.	DIP
C02	27	7 N.	68 W.	Low	2	N. 115 E.	DIP
						N. 110 W.	
C03	21	3 S.	63 W.	Low	2	N. 40 E.	DIP
C04	11	6 S.	65 W.	Low	1	N. 100 E.	DIP
C05	5	3 S.	64 W.	Low	1	N. 180 E.	DIP

TABLE A-4.--Denver Basin wells, cumulative feet of breakout for directions of breakout

[Leaders (---) indicate no data]

Direction (degrees)	C01	C02	C03	C04	C05	Total (feet)
N. 90-85 W.	---	2	---	---	14	16
N. 85-80 W.	---	2	---	---	---	2
N. 80-75 W.	---	6	---	---	---	6
N. 55-50 W.	---	---	---	---	15	15
N. 45-40 E.	2	---	---	---	---	2
N. 55-50 E.	14	84	---	---	38	136
N. 60-55 E.	2	---	---	---	---	2
N. 65-60 E.	11	346	4	---	7	368
N. 70-75 E.	---	6	---	---	---	6
N. 75-70 E.	---	457	13	12	---	475
N. 80-75 E.	---	---	3	---	7	10
N. 85-80 E.	11	203	22	25	---	261
N. 90-85 E.	---	6	3	---	---	9
Total------	40	1,112	45	30	81	1,308

TABLE A-5.--Denver Basin wells, cumulative number of breakouts for directions of breakouts

[Leaders (---) indicate no data]

Direction (degrees)	C01	C02	C03	C04	C05	Total number
N. 90-85 W.	---	1	---	---	1	2
N. 85-80 W.	---	1	---	---	---	1
N. 80-75 W.	---	1	---	---	---	1
N. 55-50 W.	---	---	---	---	1	1
N. 45-40 E.	1	---	---	---	---	1
N. 55-50 E.	2	2	---	---	1	5
N. 60-55 E.	1	---	---	---	---	1
N. 65-60 E.	2	8	1	---	1	12
N. 70-65 E.	---	1	---	---	---	1
N. 75-70 E.	---	10	3	1	---	14
N. 80-75 E.	---	---	1	---	1	2
N. 85-80 E.	1	14	3	4	---	22
N. 90-85 E.	---	1	1	---	---	2
Total----	7	39	9	5	5	65

TABLE A-6.--Denver Basin breakouts in 10° intervals

Direction (degrees)	Number of breakout	Feet of breakout
N. 90-80 W.	3	18
N. 80-70 W.	1	6
N. 60-50 W.	1	15
N. 40-50 E.	1	2
N. 50-60 E.	6	138
N. 60-70 E.	13	374
N. 70-80 E.	16	485
N. 80-90 E.	24	270
Total---------	65	1,308

TABLE A-7.--Illinois Basin wells

[Unit, low- or high-angle dipmeter tool used; DEV and AHD, approximate average values of vertical deviation and azimuth of hole drift, respectively. Type of log is either dipmeter (DIP) or fracture identification (FIL). Leaders (---) indicate no data]

Well	Location			Unit	DEV	AHD	Log
	Sec.	T.	R.		(degrees)	(degrees)	
IL1	19	3 N.	8 E.	Low	---	N. 170 W.	FIL
IL2	5	6 N.	13 W.	Low	---	N. 100 E.	FIL
IL3	36	6 N.	13 W.	---	---	N. 60 W.	FIL
KY4	21	N.	22	Low	1.5	N. 180 E.	DIP
IL5	29	4 N.	12 W.	Low	---	N. 20 E.	FIL
KY6	12	0	24	Low	1	N. 45 E., N. 125 E.	DIP
IL7	13	6 S.	2 E.	Low	1	N. 30 E.	DIP
IL8	14	6 S.	2 E.	Low	0	N. 70 E.	DIP
IL9	24	4 S.	1 W.	Low	9	N. 80 E.	FIL
IN10	11	3 S.	12 W.	Low	1	N. 60 E.	DIP
IL11	17	3 S.	8 W.	---	---	----	FIL
IN12	1	3 S.	13 W.	---	---	N. 40 E.	DIP
IL13	4	6 S.	1 W.	---	---	N. 110 E.	FIL
IL14	28	1 N.	5 W.	Low	2	N. 70 E.	DIP
IL15	31	4 S.	9 E.	Low	3	N. 65 E.	DIP
KY16	12	0	24	Low	.5	N. 170 E.	DIP
IL17	35	3 N.	12 W.	Low	---	N. 80 E.	FIL

TABLE A-8.--Illinois Basin wells, cumulative feet of breakout for directions of breakouts

[Leaders (---) indicate no data]

Direction (degrees)	IL1	IL2-3	KY4	IL5	KY6-16	IL7-8	IL9	IN10	IL11	IN12	IL13	IL14	IL15	IL17	Total (feet)
N. 90-85 W.	---	---	---	---	---	---	---	---	---	---	9	---	---	---	9
N. 75-70 W.	---	---	---	---	---	4	---	---	---	---	11	---	---	---	15
N. 70-65 W.	---	---	---	---	---	---	---	---	---	---	10	---	---	---	10
N. 65-60 W.	---	---	---	---	---	---	3	---	---	---	---	---	---	---	3
N. 55-50 W.	2	---	---	---	---	---	---	---	14	---	69	---	---	---	85
N. 50-45 W.	---	---	---	---	---	---	5	---	4	---	68	---	---	---	77
N. 40-35 W.	11	15	---	---	---	---	9	---	---	---	---	---	---	4	39
N. 35-30 W.	---	5	---	---	---	---	---	---	10	---	---	---	---	---	15
N. 30-25 W.	10	66	---	---	---	---	129	8	4	---	---	---	---	---	217
N. 25-20 W.	---	12	---	---	---	---	11	5	5	---	---	112	---	---	145
N. 20-15 W.	2	3	3	---	---	10	23	---	---	---	---	108	---	---	149
N. 15-10 W.	---	2	13	---	5	---	14	---	---	---	---	---	---	---	34
N. 10- 5 W.	---	---	77	124	42	66	45	24	---	---	---	---	---	---	378
N. 5- 0 W.	---	---	16	---	131	14	5	67	---	---	---	5	---	---	238
N. 0- 5 E.	---	---	63	35	143	78	---	72	---	82	---	54	2	3	532
N. 5-10 E.	---	---	8	---	77	102	---	15	---	88	---	---	11	4	305
N. 10-15 E.	---	3	63	40	26	57	---	---	---	152	---	---	---	3	344
N. 15-20 E.	---	8	22	---	22	19	---	---	---	---	---	---	---	---	71
N. 20-25 E.	---	---	---	19	7	45	---	---	---	3	---	---	---	---	74
N. 25-30 E.	---	---	---	---	6	64	---	---	---	7	---	---	---	---	77
N. 30-35 E.	---	---	---	---	---	17	---	---	---	7	---	---	4	---	28
N. 40-45 E.	---	---	---	---	9	50	---	---	---	---	---	---	---	---	59
Total---	25	114	265	218	468	524	244	191	37	339	167	279	17	14	2,904

TABLE A-9.--Illinois Basin wells, cumulative number of breakouts for directions of breakouts

[Leaders (---) indicate no data]

Directions (degrees)	IL1	IL2-3	KY4	IL5	KY6-16	IL7-8	IL9	IN10	IL11	IN12	IL13	IL14	IL15	IL17	Total number
N. 90-85 W.	---	---	---	---	---	---	---	---	---	---	1	---	---	---	1
N. 75-70 W.	---	---	---	---	---	1	---	---	---	---	1	---	---	---	2
N. 70-65 W.	---	---	---	---	---	---	---	---	---	---	1	---	---	---	1
N. 65-60 W.	---	---	---	---	---	---	1	---	---	---	---	---	---	---	1
N. 55-50 W.	1	---	---	---	---	---	---	---	2	---	2	---	---	---	5
N. 50-45 W.	---	---	---	---	---	---	1	---	1	---	2	---	---	---	4
N. 40-35 W.	1	1	---	---	---	---	1	---	---	---	---	---	---	1	4
N. 35-30 W.	---	1	---	---	---	---	---	---	1	---	---	---	---	---	2
N. 30-25 W.	1	1	---	---	---	---	2	2	1	---	---	---	---	---	7
N. 25-20 W.	---	3	---	---	---	---	1	1	1	---	---	5	---	---	11
N. 20-15 W.	1	1	1	---	---	1	6	---	---	---	---	5	---	---	15
N. 15-10 W.	---	1	2	---	1	---	3	---	---	---	---	---	---	---	7
N. 10- 5 W.	---	---	5	4	5	5	7	3	---	---	---	---	---	---	29
N. 5- 0 W.	---	---	3	---	7	2	1	11	---	---	---	1	---	---	25
N. 0- 5 E.	---	---	5	5	11	10	---	4	---	7	---	1	1	1	45
N. 5-10 E.	---	---	1	---	5	12	---	2	---	8	---	---	1	1	30
N. 10-15 E.	---	1	4	2	4	4	---	---	---	21	---	---	---	1	37
N. 15-20 E.	---	1	3	---	3	3	---	---	---	---	---	---	---	---	10
N. 20-25 E.	---	---	---	---	1	5	---	---	---	1	---	---	---	---	8
N. 25-30 E.	---	---	---	---	1	5	---	---	---	2	---	---	---	---	8
N. 30-35 E.	---	---	---	---	---	1	---	---	---	1	---	---	1	---	3
N. 40-45 E.	---	---	---	---	1	1	---	---	---	---	---	---	---	---	2
Total---	4	10	24	12	39	50	23	23	6	40	7	12	3	4	257

TABLE A-10.--Illinois Basin breakouts in 10° intervals

Direction (degrees)	Number of breakouts	Feet of breakout
N. 90-80 W.	1	9
N. 80-70 W.	2	15
N. 70-60 W.	2	13
N. 60-50 W.	5	85
N. 50-40 W.	4	77
N. 40-30 W.	6	54
N. 30-20 W.	18	362
N. 20-10 W.	22	183
N. 10- 0 W.	54	616
N. 0-10 E.	75	837
N. 10-20 E.	47	415
N. 20-30 E.	16	151
N. 30-40 E.	3	28
N. 40-50 E.	2	59
Total------	257	2,904

TABLE A-11.--Basin breakout statistics

	Denver Basin	Illinois Basin
Feet of breakout--------------	1,308	2,904
Number of breakouts-----------	65	257
Number of wells---------------	5	17
Feet of breakout per well-----	261.6	170.9
Feet of breakout per breakout-	20.1	11.3
Number of breakouts per well--	13	15.1

TABLE A-12.--Well statistics

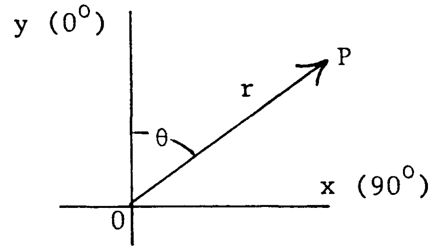
[Depth of drilling is the depth of the well, interval of logging is the part of the well that was logged, and interval of breakout is that part of the logged interval where breakouts were found. Common datum is mean sea level]

Well	Elevation of well (feet)	Depth of drilling (-feet)	Interval of logging (feet)		Interval of breakout (feet)	
			From	To	From	To
Denver Basin						
CO1	5299	-2642	-1589	-2619	-1942	-2531
CO2	4882	-2210	4361	-2209	-3552	-1668
CO3	5440	-2513	-1350	-2509	-1462	-2281
CO4	6110	-2707	-1777	-2673	-1937	-2537
CO5	5357	-2874	-1743	-2869	-1779	-2691
Illinois Basin						
IL1	451	-1054	386	-1052	-8	-913
IL2	485	-3567	-1849	-3556	-3138	-3156
IL3	444	-3584	-944	-3584	-2090	-2430
KY4	475	-6173	-794	-2793	-1035	-2575
IL5	522	-4591	-1366	-4590	-2256	-4473
KY6	436	-2140	-138	-2138	-242	-1831
IL7	437	-2492	-258	-2300	-610	-2259
IL8	419	-1672	-977	-2270	-1101	-2258
IL9	509	-7575	-3475	-7565	-4171	-6813
IN10	458	-2750	-788	-2786	-1189	-1988
IL11	428	-5062	-3262	-5055	-2106	-2446
IN12	400	-3010	-1008	-2008	-1382	-2214
IL13	418	-4182	-2166	-4180	-2652	-3923
IL14	497	-3528	-1748	-3528	-1893	-2478
IL15	400	-2996	-2496	-2944	-2522	-2578
KY16	440	-2153	-353	-2150	-1051	-1801
IL17	440	-2950	-1254	-2947	-1254	-1304

APPENDIX B

METHOD OF COMPUTING MEAN AND ANGULAR DEVIATION OF BREAKOUT DATA

Breakouts are treated as two-dimensional vectors. Vector direction is breakout azimuth and magnitude (vector length or frequency) is the number of breakouts or feet of breakout at a given azimuth. Vector direction and frequency are expressed as the polar coordinates, vector angle θ and radii quantity r. For convenience, vector angles θ are measured clockwise from 0°. Assume the positive X direction as east (90°) and the positive Y direction as north (0° or 360°). In the example below, vector $\overline{OP}$ has a direction of angle θ and a length of r:



Each breakout vector has two values of r: (1) number of breakouts and (2) feet of breakout. With two measures of vector length for each vector direction, two calculations of mean direction and mean angular deviation can be computed for each data set. A data set can be either the breakout vectors from an individual well or from all the wells in a basin. Breakout vectors within a data set can be treated as either individual vectors or they can be grouped in intervals of a specified number of degrees. In the study of Denver and Illinois Basin breakouts, vectors in the basin data sets were grouped in 10° intervals.

A data set of breakout azimuths is considered as an axially symmetric, circular-normal distribution of vectors that is unimodal in the range of 180°. To confirm that the distribution is approximately normal and unimodal, breakout data can be plotted as a frequency rose diagram. Within the distribution of breakout vectors, the frequencies of vectors with the same azimuths are summed. Therefore, quantity r is a function of the sum of the vector frequencies at angle θ on a unit circle of radius 1.

With circular distributions of directional data where vectors are axially symmetric, as with breakout data, half of the circular distribution will cancel the other half (Curray, 1956). To avoid this and thereby produce a nonsymmetric periodic distribution, only half of the circular distribution with a range of 180° is considered. Vector angles within the half circle are then doubled (2θ) to achieve a distribution of the data over the full 360° period of the unit circle. This will produce a resultant mean of twice the tangent of the resultant (Curray 1956). If data are being grouped in degree intervals, the group midpoint or angle θ is doubled. Vector frequencies will correspond to doubled angles (2θ).

The following method details the procedure used to compute mean direction of the resultant vector at the 95-percent confidence level and the mean angular deviation of a breakout data set. At the 95-percent confidence level the true circular mean will be within ±° (the confidence interval) of the predicted mean direction (Spiegel, 1961). Angular deviation, like standard deviation and variance, is a measure of the dispersion of the data about the computed or predicted mean direction. When the angular deviation is <50°, 67 percent of the data will be within ±° the angular deviation of the predicted mean direction; and if the angular deviation is >50° the percentage of data will decrease gradually from 67 to 45 percent (Batschelet, 1965). In the following example, mean direction and angular deviation are calculated for Denver Basin breakout azimuths of feet of breakout. There are 1,308 ft of breakout distributed among 13 breakout azimuths. The 13 breakout azimuths are grouped in eight 10° intervals (see tables A-4 and A-6).

1. Breakout azimuths (vector angles θ) are grouped in 10° intervals in the range of 180° with group midpoints (θ_i).

2. Vector frequencies (feet of breakout) of breakout vectors within each 10° interval are summed to produce an interval frequency (f_i).

3. Interval midpoint angles (θ_i)are doubled ($2\theta_i$).

4. The population size (N) is the sum of the interval frequencies: $N = \Sigma f_i$ N=1,308 ft (see table A-4).

5. Compute the north-south and east-west trigonometric components of the resultant vector:

$$\text{N-S component} = \Sigma f_i \cos 2\theta_i$$

$$\text{N-S component} = -1001.5748$$

$$\text{E-W component} = \Sigma f_i \sin 2\theta_i$$

$$\text{E-W component} = 687.3422$$

6. Compute the Cartesian or rectangular coordinates $\bar{C}$ and $\bar{S}$ of the resultant mean:

$$\bar{C} = 1/N \; \Sigma f_i \cos 2\theta_i$$

$$\bar{C} = -0.7657$$

$$\bar{S} = 1/N \; \Sigma f_i \sin 2\theta_i$$

$$\bar{S} = 0.5254$$

7. Compute the magnitude or length ($\bar{R}$) of the resultant vector:

$$\bar{R} = (\bar{C}^2 + \bar{S}^2)^{1/2}$$

$$\bar{R} = 0.9286997$$

$\bar{R}$ is a measure of the concentration of the data about the resultant mean (Batschelet, 1965). A simple test of dispersion is $N-\bar{R}$. Dispersion is small or close to 0 if $\bar{R}$ is nearly large as N (Watson, 1966, 1970). The value of N is 1 (the radius of the unit circle).

8. The grouping of breakout vectors in degree intervals will not affect circular mean, but it will influence the value of angular deviation. Therefore, before calculating angular deviation, $\bar{R}$ must first be corrected ($\bar{R}_c$) (Batschelet, 1965).

$$\bar{R}_c = \bar{R} \frac{\beta}{\sin \beta}$$

Where β is half the arc of the group interval in radians. If breakout vectors are grouped in 10° intervals the doubled group interval will equal 20°, then:

$$\beta = 10° \text{ or } 0.1745 \text{ radians}$$

$$\bar{R}_c = 0.9287 \frac{0.1745}{0.1736}$$

$$\bar{R}_c = 0.9335$$

9. Compute mean direction or polar angle of the resultant vector ($\bar{\theta}$).

$$\bar{\theta} = 1/2 \ (\arctan \bar{S}/\bar{C}),$$

or

$$\cos 2\bar{\theta} = \bar{C}/\bar{R}, \ \sin \bar{\theta} = \bar{S}/\bar{R},$$

and

$$\tan 2\bar{\theta} = \sin 2\bar{\theta} \ / \ \cos 2\bar{\theta}$$

$$\bar{\theta} = 1/2 \ (\arctan - 0.6863)$$

$$\bar{\theta} = 1/2 \ (-34.4603)$$

$$\bar{\theta} = -17.2302°.$$

10. Compute the angular deviation (corrected) of the data about the resultant mean ($\bar{\theta}$).

$$A_c = 1/2 \ \sqrt{2(1 - \bar{R}_c)}$$

$$A_c = 1/2 \ \sqrt{2(1-0.9335)}$$

$$A_c = 0.1823 \text{ (radians)}$$

11. Convert radians to degrees.

$$A°_c = 180 \ A_c/\pi$$

$$A°_c = 10.4476°$$

12. Compute the 95-percent confidence limits of $\bar{\theta}$. Because $N \geq 30$ the confidence coefficient is 1.96.

$$0.95 = \bar{\theta} \pm 1.96 \; (A_c / \sqrt{N})$$

$$0.95 = -17 \pm 1.96 \; (10.4476 / \sqrt{1,308})$$

$$0.95 = -17° \pm 0.6°$$

13. Convert $-\bar{\theta}°$ to azimuthal degrees in the range of 0° to 180°. First, determine approximately where $\bar{\theta}$ will lie within this range. This can easily be done by visually interpolating the location of $\bar{\theta}$ on the frequency rose diagram of breakout azimuths. If $\bar{\theta}$ is between 0° and 45° then $\bar{\theta} = \bar{\theta}$. If $\bar{\theta}$ is between 45° and 135° then $\bar{\theta} = \bar{\theta} + 90°$. If $\bar{\theta}$ is between 135° and 180° then $\bar{\theta} = \bar{\theta} + 180°$.

From the rose diagram of feet of breakout in figure 2, it can be seen that the predicted or computed mean direction of breakout for feet of breakout will be between N. 45° and 90° E. By adding 90° to -18° ($\bar{\theta}$), $\bar{\theta}$ = N. 73° E.