equation (1).

The definition of angular measurements requires a special note for the two reference frames. We use the term "azimuth" to refer to a direction measured east from north in the geographic coordinate system. We do not use the term "azimuth" in the borehole coordinate system, since north is not a special direction in that coordinate system. Rather, all angles are measured counterclockwise from the **I** axis when one looks down the **K** axis. We use the word "azimuth" to refer to angles measured only in the geographic coordinate system and the word "angle" to refer to angles measured in the borehole coordinate system. When the two coordinate systems coincide, then the "azimuth" is calculated by subtracting the "angle" from 90°:

$$\text{azimuth} = 90^\circ - \text{angle}. \tag{2}$$

Identification of Breakouts

Here we discuss criteria for identification of breakouts, and calculation of breakout azimuths, given either oriented four- or six-arm caliper data. Oriented four- or six-arm caliper data are measured on a variety of different well-logging tools, such as low-angle dipmeters, high-angle dipmeters, formation microscanners/microimagers, and stratigraphic high-resolution dipmeter tools (SHDTs).

Plumb and Hickman [1985] examined the validity of using four-arm dipmeters to identify borehole breakouts. They logged a well in Auburn, New York, twice with a four-arm dipmeter and once with a borehole televiewer. The borehole televiewer is an acoustic logging tool that provides high-resolution information about borehole elongation and the distribution of natural fractures in wells [*Zemanek et al.*, 1970]. The acoustic transit time can be used to construct detailed borehole cross sections. By comparing the orientation of breakouts from the four-arm dipmeter with borehole cross sections constructed from the televiewer data they found that the four-arm dipmeters generally had their long axes aligned with the breakouts. This is a critical observation, since borehole televiewer logs are not commonly run in most drill holes, and many wells logged with four-arm dipmeters lack the more detailed televiewer observations.

Plumb and Hickman [1985] defined five criteria they used to identify zones of breakouts from four-arm dipmeter logs:

1. The tool rotation stops in the zone of elongation.
2. The caliper arm difference is greater than 0.6 cm.
3. The smaller of the caliper readings is close to bit size, or if the smaller caliper reading is greater than bit size, it should exhibit less variation than the larger caliper.
4. The length of the breakout zone is greater than 30 cm.
5. The direction of elongation should not consistently coincide with the azimuth of the high side of the borehole when the hole deviates from vertical.

From our experience with examining deviated boreholes we have slightly modified *Plumb and Hickman*'s [1985] breakout selection criteria. The new criteria used are as follows:

1. The tool rotation stops in the zone of elongation. Dipmeter logs record either pad 1 azimuth or the relative bearing of pad 1, or both. The pad 1 azimuth is the **XYZ** azimuth of the number 1 dipmeter pad. The relative bearing is the **IJK** angle between the high side of the hole and pad number 1. Both of these measure the orientation of the tool in the hole. Our selection criterion for nondigital data sets is that the maximum variation of either measurement should be less than 10°. When digital data are available, the standard deviation of either data type must be less than 1.25°. We use *Mardia*'s [1972] work in the statistics of angular data to calculate the average borehole elongation direction and its standard deviation for a particular section of hole.
2. The largest and smallest caliper arms should be at least 5% different from each other.
3. The smallest caliper arm should be larger than or equal to the bit size and smaller than 1.1 times the bit size.
4. The standard deviation of each caliper arm over a breakout interval should be less than 2.54 cm (1 inch).
5. The length of the breakout zone should be at least 3 m.
6. The maximum difference between the bit size and the largest caliper arm should be 7.62 cm (3 inches).

Criterion 1 of *Plumb and Hickman* [1985] was tightened to be more quantitative regarding the variation in the quality of the breakout direction. Criterion 2 was changed to demand a 5% difference between the caliper arms instead of a 0.6 cm difference. This criterion is more flexible for boreholes of different radii. Criterion 3 was slightly changed to state that the smallest caliper