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STRUCTURAL GEOLOGIC INTERPRETATION

FROM RADAR IMAGERY*

by

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Structural geologic interpretations from radar imagery

by

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Abstract

Certain structural geologic features may be more readily recognized on sidelooking airborne radar (SLAR) imagery than on conventional aerial photography or other remote sensor imagery or by ground observations. SLAR systems look obliquely to one or both sides. SLAR images resemble aerial photographs taken at low sun angle, with the sun directly behind the camera, but differ from them in geometry, resolution, and information content. Radar operates at much lower frequencies than the human eye and camera or infrared sensors, and thus "sees" differently. The lower frequency enables it to penetrate most clouds and some precipitation, haze and dust, and some vegetation. Radar provides its own illumination which can be closely controlled in intensity and frequency. It is narrow band, or essentially monochromatic.

Low relief and subdued features are accentuated when viewed from the proper direction. Runs over the same area, at significantly different directions (more than 45°) from each other, show that images taken in one direction may emphasize features that are not emphasized on those taken in the other direction; optimum direction is determined by the features desired to be emphasized for the purpose of the study.

Lineaments interpreted as faults stand out on radar imagery of central and western Nevada. Folded sedimentary rocks cut by faults can be clearly seen on radar imagery of northern Alabama. In these areas, certain structural

and stratigraphic features are more pronounced on the radar imagery than on conventional photography, and the radar imagery materially aids structural interpretation.

Introduction

In 1965, the U. S. Geological Survey, working with the National Aeronautics and Space Administration, obtained high quality sidelooking airborne radar (SLAR) imagery of selected areas of geologic interest with equipment developed for the U. S. Army Electronics Command. This paper reports on the structural interpretations of three of these areas. The Silver Peak Range-Fish Lake Valley area in Nevada and the Coosa River Valley area in Alabama, are covered by published 1:250,000 scale geologic maps (Albers and Stewart, 1965, Whitlow, 1962); no published geologic map, at a scale of 1:250,000 or larger, exists of the Chalk Mountain-Fairview Peak, Nevada area, although it has been mapped by the Geological Survey as part of a cooperative effort with the Nevada Bureau of Mines (Willden and Speed, 1968). The structural interpretations were done without examination of the published geologic maps or any other geologic maps or information and the results plotted on 1:250,000 topographic sheets. The interpretations were then compared with published and other information, and the Nevada areas were visited in the spring of 1968; in addition, the interpretations have been discussed with my Geological Survey colleagues John P. Albers, John H. Stewart, Jesse W. Whitlow, and C. Ronald Willden, who mapped the areas and Robert Mixon, who has worked in the Coosa River area. Mr. Stewart kindly loaned aerial photographs of the Silver Peak Range-Fairview Valley area, and aerial photographs of the Chalk Mountain-Monte Christo Mountains area were made available through the courtesy of the MacKay School of Mines of the University of Nevada,

especially Professor D. B. Slemmons. The paper has likewise benefited from discussions with and reviews by Professors Slemmons and Louis F. Dellwig of the University of Kansas and my USGS colleagues Raymond Fary, Allan Kover, and Gwendolyn W. Luttrell. Their assistance is greatly appreciated; all responsibility for errors and flights of fancy in interpretation is mine, however.

Interaction between electromagnetic radiation and geologic materials

The interaction between electromagnetic radiation (EMR) and matter is complex and imperfectly known in many of its details. EMR may be reflected from or penetrate geologic materials; generally, however, neither complete reflection nor penetration is obtained. The radar signal intensity that is received is a measure of the amount of EMR returned from the irradiated surface; this is a mix of the surface configuration (large-scale features such as hills and valleys) and roughness (small-scale features, on the order of millimeters and centimeters), chemical and physical composition of the surface materials, and scan direction. Of these, surface configuration and roughness determines which of the two types of reflection, <u>diffuse</u> or <u>specular</u> (Beckmann and Spizzichino, 1963, p. 3; ASP, 1966, p. 1022; Rydstrom, 1967, p. 432) takes place. Specular or mirrorlike reflection is produced by surfaces that are rough at the wavelength of the EMR and which scatter the EMR and reflect part of it back towards the radar. Although the relationship between wavelength and roughness is not precisely known, empirical observations suggest that features smaller than one-fourth to one-half of the wavelength of the EMR reflect specularly and thus appear "smooth" to the radar, and those larger than that scatter the EMR and appear rough. The shapes of the protuberances, as well as their size, and the angle of incidence of the EMR influence the type of reflection. The proportions of the EMR that are reflected and penetrate depend mainly on the dielectric constant at the frequency of the EMR. The dielectric constant is strongly frequency dependent. At a given frequency, however, the dielectric constant depends on the chemical composition and physical state of the material. The direction of flight with respect to the terrain has considerable influence on the radar return; imagery from flights at 90° or 180° from each other of some areas may be dissimilar and give the appearance of not being of the same area. In other areas the flight direction appears to have very little influence (Dellwig, in press).

EMR in the portion of the spectrum used by radars is less affected by dust and moisture particles in the atmosphere than EMR at the shorter wavelengths of the infrared and visible portions, and penetrates most cloud cover, mist, and haze. Limited penetration through vegetation and dry sand and soil may be achieved with the longer wavelength radar EMR.

EMR radiated from a radar antenna may be plane, circularly, or elliptically polarized, depending on the transmitter characteristics and antenna design. The radar set may be designed to receive the same polarization as transmitted or different polarization of the EMR reflected from the irradiated surface and returned to the set.

The EMR striking the surface may, and probably usually does, undergo changes in polarization as a result of its interaction with geologic materials, vegetation, man-made structures, and other features. Although the exact relationships between these features and polarization changes is not yet known, examination of imagery recording two or more polarizations shows that some features markedly change the polarization of the return EMR from that transmitted, and others do not. Structural geologic features do not seem to appear greatly different on images of different polarization, however.

The radar system with which this imagery in this report was taken is capable of transmitting either horizontally or vertically plane polarized EMR and receiving both the like or orthogonally (cross) polarized return. The like polarized image was produced with horizontally polarized return EMR and the cross polarized image was produced simultaneously by recording the vertically polarized return EMR. For a more complete discussion of side-looking radar as a remote sensor, see Moore (1966).

SLAR imagery and its interpretation

SLAR imagery superficially resembles conventional small scale aerial photography taken at low sun angles. The similarity ends there, however; SLAR imagery differs from aerial photography in geometry, resolution, "visualization," and information content. By "visualization" is meant the way in which SLAR "sees" objects or areas in comparison with that in which a camera or human eye sees them. Camera films record EMR ranging in wavelength from about 300 millimicrons (mμ; 10^{-6}mm) to about 1000 mμ, either across that entire spectral range in shades of gray (panchromatic); in color; or, by using various film/filter combinations, in narrow bands (as narrow as 50 mμ). The human eye responds to EMR from about 480 mμ to 760 mμ. Radars operate at much longer wavelengths, generally from about 0.5 mm to 10 m, and thus "see things in a different light." The EMR transmitted by radars is essentially a single frequency, and thus corresponds to a very narrow band in the visible portion of the spectrum. Because of the much longer wavelength of radar EMR features that appear textured to the human eye or when viewed on conventional camera film may appear to be smooth on

[redacted]

the radar image. Also, features that show diffuse texture at short wavelengths can be specular at long wavelengths.

The SLAR image is made up of a large number of individual, contiguous scan lines. As the SLAR moves over the ground, the film on which the image is recorded moves past the CRT at a rate proportional to the speed of the SLAR so that the azimuth and range scales are approximately equal. Thus, if the vehicle and film speeds are properly synchronized and the vehicle is following a straight path, the azimuth scale will be uniform along the film and from near to far range across the film, and will equal the range scale. The scan-line method of building up a radar image produces an entirely different geometry than that associated with aerial photographs. In the range direction, the "constant altitude" scale is uniform, but features above a base (arbitrary) are displaced toward the near range, and those below the same arbitrary base are displaced toward the far range, leading to scale variations in the range direction. In practice, it is difficult to synchronize the craft and film speeds and to hold the aircraft on a straight course, so that change in azimuth scale along the film and from near to far range across the film, and disparity between range and azimuth scale, are the rule. For a more complete discussion of radar imagery see, for example, Reeves (1968, p. 322-328).

As with aerial photographs, SLAR imagery should be oriented so that the radar shadow falls toward the interpreter. When so oriented, hills and valleys may be properly identified. To study linear features turning the image so that the eye looks along the feature is a useful technique in tracing it and correlating discontinuous segments.

Radar imagery has several features not found on conventional photographs.

One of these is "layover" which occurs along the near range side and results in the radar signal reaching and being reflected from the crests of steep-sided topographic highs before reaching and being reflected from their bases (on the side towards the radar). Layover is especially noticeable at the top (near range) of figures 2 and 3. Another feature is radar shadow, produced by topographic highs blocking out the radiation from steep back (away from the SLAR) slopes. The farther away from the SLAR, the smaller the angle of incidence of the radiation, and hence, the more pronounced is the shadowing. Radar shadows are prominent on the steep slopes of the Silver Peak Range (figure 3).

Silver Peak Range -- Fish Lake Valley area

The Silver Peak Range is in south central Esmeralda County, Nevada. Fish Lake Valley adjoins the Silver Peak Range on the southwest and straddles the California-Nevada border, which diagonally crosses the lower part of figure 2. The geology of the portion of the area in Nevada was mapped in reconnaissance fashion by Albers and Stewart (1965) as part of their study of Esmeralda County, and the following description of the geology is from their map. SLAR imagery of the northwestern part of the Silver Peak Range and central part of Fish Lake Valley was acquired on Flight 99, October 29, 1965. The SLAR aircraft flew southerly direction, east of the area, and imaged to the west. The aircraft was turning during most of the run over the area, so that the azimuth scale varies from near range to far range (top to bottom of the image). The average (at the center of the strip) azimuth scale of the original negative is approximately 1:190,000, and the range scale is approximately 1:210,000. The area of the radar image in figure 2 is approximately 36 km (22 miles) north-south and approximately 18 km (11 miles) east-west, or about 240 square miles. From about 10 to 15 percent of the near range is not usable owing to severe distortion and layover, so that the effective area is about 200 square miles.

The Silver Peak range is moderately high and rugged. The highest point in the Range, Silver Peak, is 2880 m (9447 feet) above mean sea level and the Salt Flats in Fish Lake Valley are just over 1400 m (4700 feet) above msl. Slopes are steep, and produce pronounced radar shadows. Much of the area is inaccessible by vehicle, even with 4-wheel drive. A good gravelled road extends up McAfee Canyon, and a road extends from the Silver Peak (east) side of the range north to the headwaters of Argentite Canyon, along the east side of the area covered by the radar image. Another road crosses the range from Fish Lake Valley to Silver Peak, via the unnamed canyon along the south of Rhyolite Ridge that heads north of Red Mountain, and Coyote Canyon (not on the map). The minimum distance between the Rhyolite Ridge-Red Mountain and McAfee Canyon roads is 15 km (9 miles). The Silver Peak range is dominantly granite to granodiorite, of middle Mesozoic to Tertiary age that has intruded Cambro-Ordivician sedimentary rocks. Both the granitic and sedimentary rocks are capped by volcanic rocks ranging from basaltic to rhyolitic composition and flows to ash falls in origin. All of these rocks are cut by faults.

Fish Lake Valley consist of normal valley fill material, eroded from the adjacent ranges. Much of the center of the valley is flat and floored by salt deposits.

A series of north to northwest-trending and east-trending linear features stand out on the radar image (Fig. 2a) and are plotted on the cross-polarized radar image (Fig. 2b). Many of these features coincide with or are extensions of faults mapped by Albers and Stewart (1965). Others are not shown on Albers' and Stewart's map; some, however, were mapped by them on their 1:62,500 field sheets, but were omitted because they were minor faults, to avoid clutter on the published map, or it was uncertain that they are faults.

The most pronounced linear features extend eastward up Piper Canyon and across the main part of the range into Argentite Canyon and south-southeasterly down Icehouse Canyon and neighboring canyons to the west. An altered zone, including areas of quartz cemented fault breccia, where numerous prospect pits have been sunk and short adits driven, occurs along a lineament 3 km (2 miles) north of and parallel to McAfee and Piper Canyons. McAfee Canyon is interpreted by Albers and Stewart (1965) to coincide with a major fault. A major linear feature, here called the "Spring Fault," passes through the "Jeff Davis" and "Blind" springs (shown on the Piper Peak, Nevada-California 15 minute quadrangle). The Spring Fault appears to be an extension of the inferred Piper Canyon fault, perhaps offset slightly by the inferred Icehouse Canyon-Piper Peak fault system. Some of these linear features are without the surficial expressions of faults; others are of dubious origin. The parallelism of these linear features suggests, however, that they are shear zones or pronounced joint sets related to the major structural features of the area.

The contact between alluvial fan material extending from the Silver Peak Range and the White Mountains, and the fine grained valley fill in the central part of Fish Lake Valley, shows distinctly on Figure 2a. Within the fine-grained material, several distinct units are evident. The alluvial fan material is a diffuse reflector, and returns a significant amount of EMR to the radar. The fine grained material is a specular reflector, and reflects most of the EMR away from the radar.

Chalk Mountain - Fairview Peak area

The Chalk Mountain-Fairview Peak area is in southeastern Churchill County, Nevada, about 57 km (35 miles) east-southeast of Fallon. The area was mapped in the 1930s by F. C. Schrader and E. E. Fairbanks (report in the files of the U. S. Geological Survey) and remapped by C. R. Willden in 1967. Sidelooking airborne radar imagery of the Chalk Mountain-Fairview Peak Slate Mountain area was acquired on Flight 95, October 29, 1965 (Fig. 3). The aircraft flew south along a line east of the area, and "looked" (imaged) to the right, or west. The film scale of this imagery is approximately 1:145,000 in the range direction and 1:140,000 in the azimuth direction. The area, from the north end of Chalk Mountain to the south end of the southern extension of the Monte Christo mountains is approximately 55 km (34 miles) along and 15 km (9 miles) wide, or about 800 square kilometers (300 square miles). The usable portion of image, excluding the highly distorted 10 to 15 percent of the near range, is about 700 square kilometers (260 square miles).

The following description of the geology and geologic map of the northern part (Churchill County) of the area is from Willden and Speed (1968), that for the northwestern part of Nye County from Kleinhampl and Ziony (1967), and for the Mineral County portion from Ross (1961).

The northern part of Chalk Mountain is underlain by volcanic rocks cut by granodiorite, and the southern part by limestone, also cut by granodiorite. Fairview Peak and the northern flank of Slate Mountain are underlain by slate, and the western flank by granodiorite. Older Tertiary volcanic flows, mostly basalt and andesite, are exposed on the southern and extreme western flanks of Slate Mountain. The western slope, between the main hill mass and Fairview Valley, is a bajada of older Quaternary alluvium. The narrow valley, between Fairview Peak-Slate Mountain and the unnamed low hills to the east, is also underlain by older Quaternary alluvium. The fault scarp produced during the 1954 Fairview Peak-Dixie Valley earthquake formed mostly in this alluvium. This scarp is clearly visible on a duplicate positive transparency examined on a viewing table, and barely discernible on a high-quality paper print. The sedimentary, volcanic, and intrusive rocks are cut by a series of faults ofprobably Quaternary age, belonging to the present Basin and Range structural framework.

A series of north- and northwest - trending linear features stand out on the radar images (Figures 4 and 6). The most prominent north-trending linear feature extends from east of Slate Mountain southward for about 11 kilometers and possibly for about 24 kilometers. Another but less prominent and, thus, less clearly a structural feature, extends southward past the crest of Fairview Peak across Bell Flat and on into the Monte Christo Mountains. Northwest trending linear features cross the range, just south of Fairview Peak and farther south between Fairview Peak and Slate Mountain. Parallel features cut the Monte Christo Mountains and are apparent in the low hills that jut southwest from the Monte Christo Mountains into Gabbs Valley.

Altered zones, quartz and calcited cemented breccia, and jasper veins occur along the linear features north of the "Big Wash" between Fairview Peak and Slate Mountain. If these features are not faults, they appear nonetheless to have served as conduits for altering and mineralizing solutions. The southwestern extension of the Fairview Peak fault can be seen in the

Big Wash; it trends N 40 E and dips 70°NW. The SE side appears to be upthrown.

Coosa River Valley

The area shown in Figure 4 is south and southwest of Gadsden, Alabama. The Coosa River flows northward and cuts through ridges of sedimentary rocks of Silurian (Clinton) and older ages. The area was mapped by Whitlow (1962) as part of his investigation of Silurian sedimentary red iron ore beds in Alabama, Georgia, and Tennessee. SLAR imagery was acquired on Flight 106, November 10, 1965. The plane was flying easterly and looking southerly. The plane flew in a broad arc concave to the south, leading to some distortion in the azimuth direction from top to bottom. The average scale of the imagery in the azimuth direction is approximately 1:190,000 and in the range direction is approximately 1:210,000.

In the area covered by the SLAR image, the Coosa River flows southward from Gadsden and cuts through or goes around a series of ridges of Silurian Red Mountain Formation and older rocks. From north to south, the principal ridges are Canoe Creek Mountains - Dunaway Mountain, Pine Ridge-Hines Mountain, Beaver Creek Mountains - Greens Creek Mountains, and Shoal Creek Mountains. The narrow to moderately wide valleys, from north to south Canoe Creek Valley, the valley of Parmeter Creek, and Shoal Creek Valley separate the ridges. The strata in the ridges and underlying the valleys are folded into anticlines and synclines, some of which appear to plunge to the east and northeast, and cut by east northeast trending thrust and high angle reverse faults. Direction of movement along the faults is north-northwest.

Linear features that can be seen on the radar image and that appear to offset the strata are interpreted as faults. These faults appear to be extensions of faults shown on the geologic map of Alabama (Adams et al, 1926).

Conclusions

Many linear features are apparent on radar imagery. Some of these, but generally only a small fraction of the total number, can be identified as faults with a high degree of certainty. When radar imagery is used with other remote sensor data -- infrared imagery and various types of aerial photographs -- the assurance with which interpretation of the linear and other features on the radar imagery as specific geologic structures can be made is greatly increased. The chief value of radar imagery (and other remote sensor data) is to call attention to anomalous features for further investigation and identification by all possible means. The radar imagery provides a synoptic view, with uniform illumination, of a large area. The low angle of the radiation (illumination) with the surface enhances subtle topographic and other features. The longer wavelength enables it to penetrate clouds, dust, haze, and a limited amount of vegetation and other surface material and produce a sharp image. The radar image directs the attention of the geologist to areas and features that merit further detailed study, and may serve to point out other areas that do not need to be studied in detail.

Although the radar images are distorted by variations in aircraft speed and altitude above the surface, by aircraft turns, and by displacement of topographic features, it is possible to readily correlate them with topographic maps and to easily transfer geologic features from the radar images to the topographic bases. Radar imagery of areas where it shows structural features, when used with care and discretion, should enable a geologist doing field mapping to obtain a better and more complete structural picture in a shorter time than is possible without its use.

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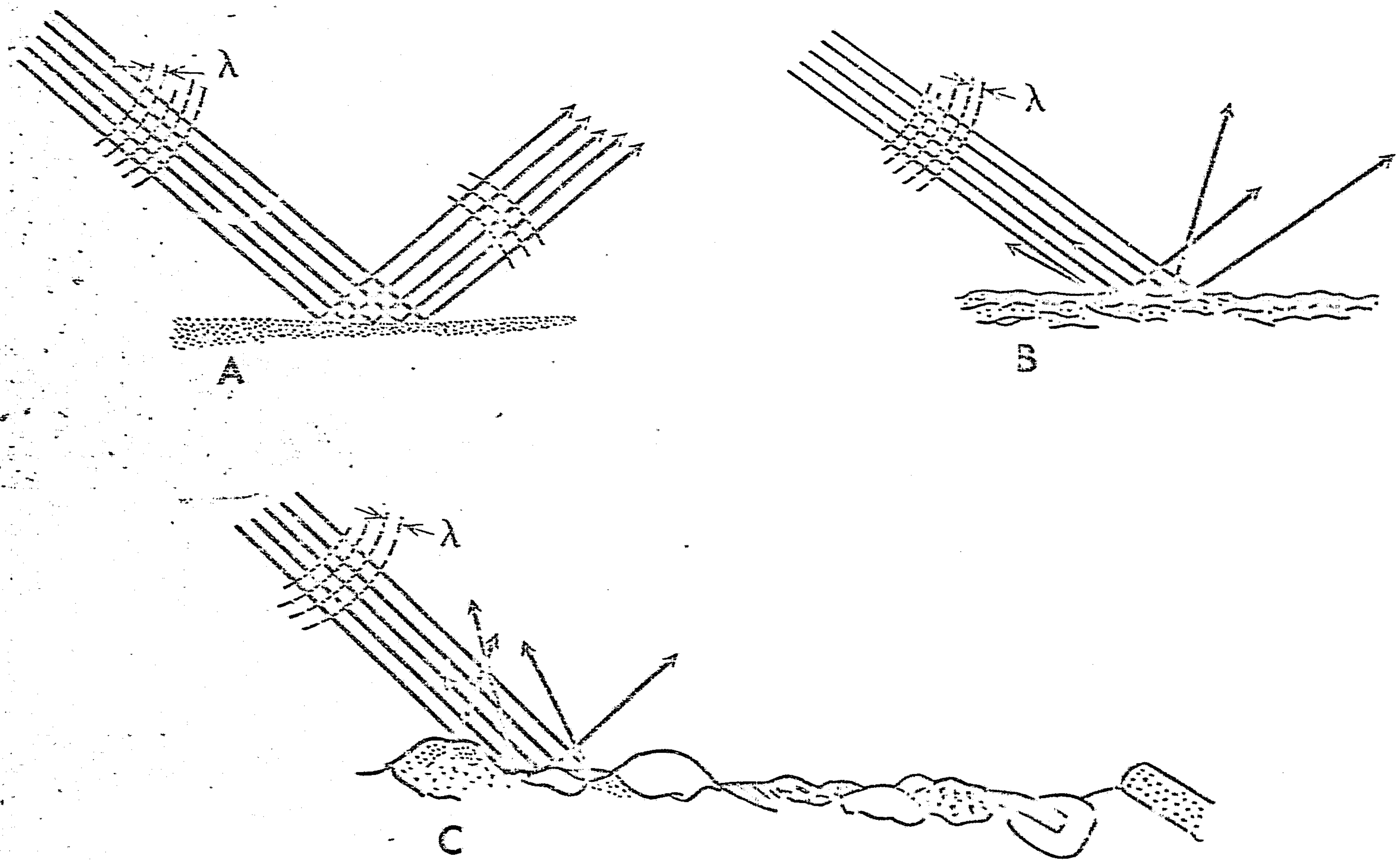

Figure 1: Specular and diffuse reflection. A. A smooth surface at the wavelength of the EMR. B. A moderately rough surface at the wavelength of the EMR. C. A very rough surface at the wavelength of the EMR.

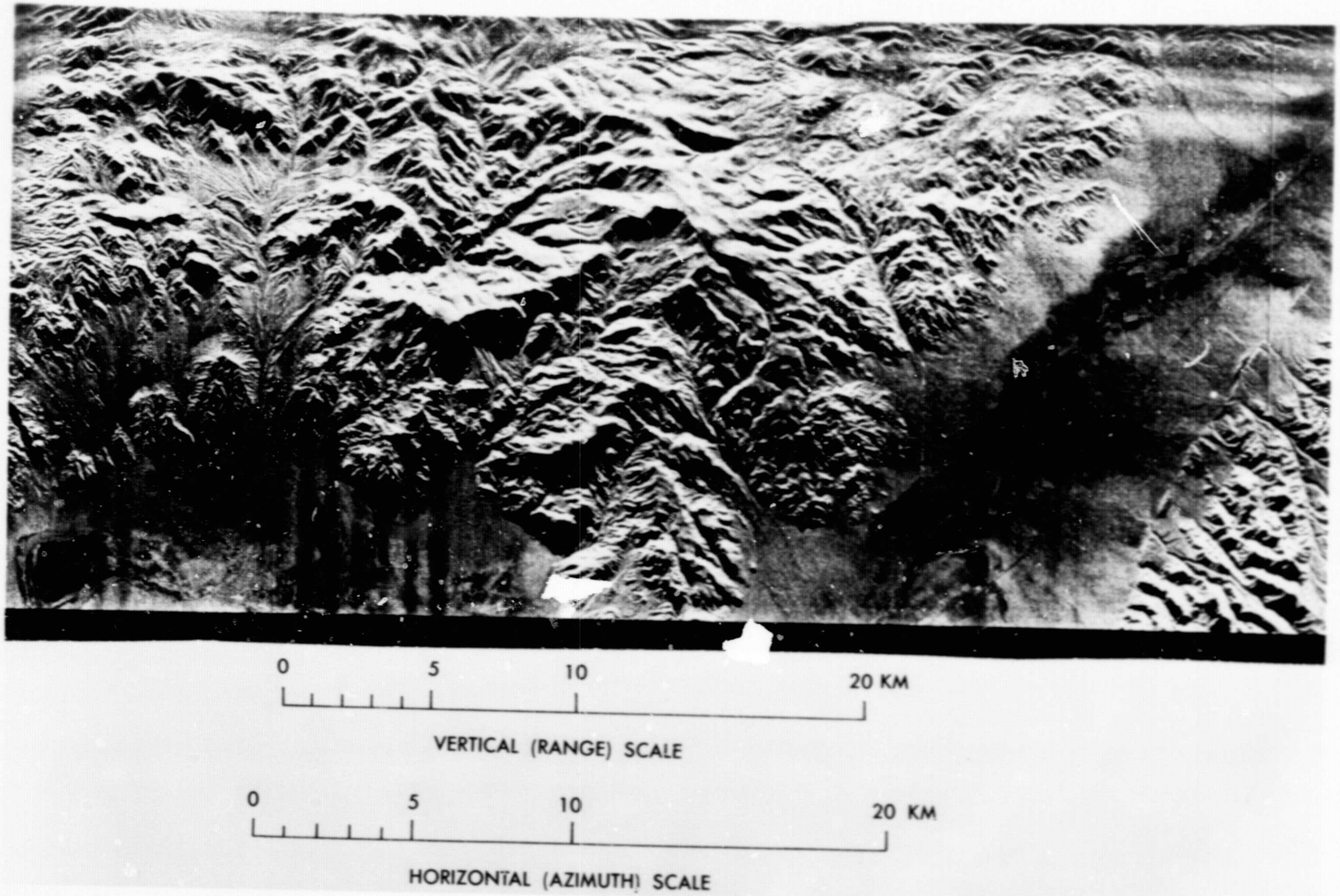

Figure 2A.: Sidelooking radar image of the Silver Peak Range-Fishlake Valley area, Esmeralda County, Nevada and Mono County, California. Like polarized image.

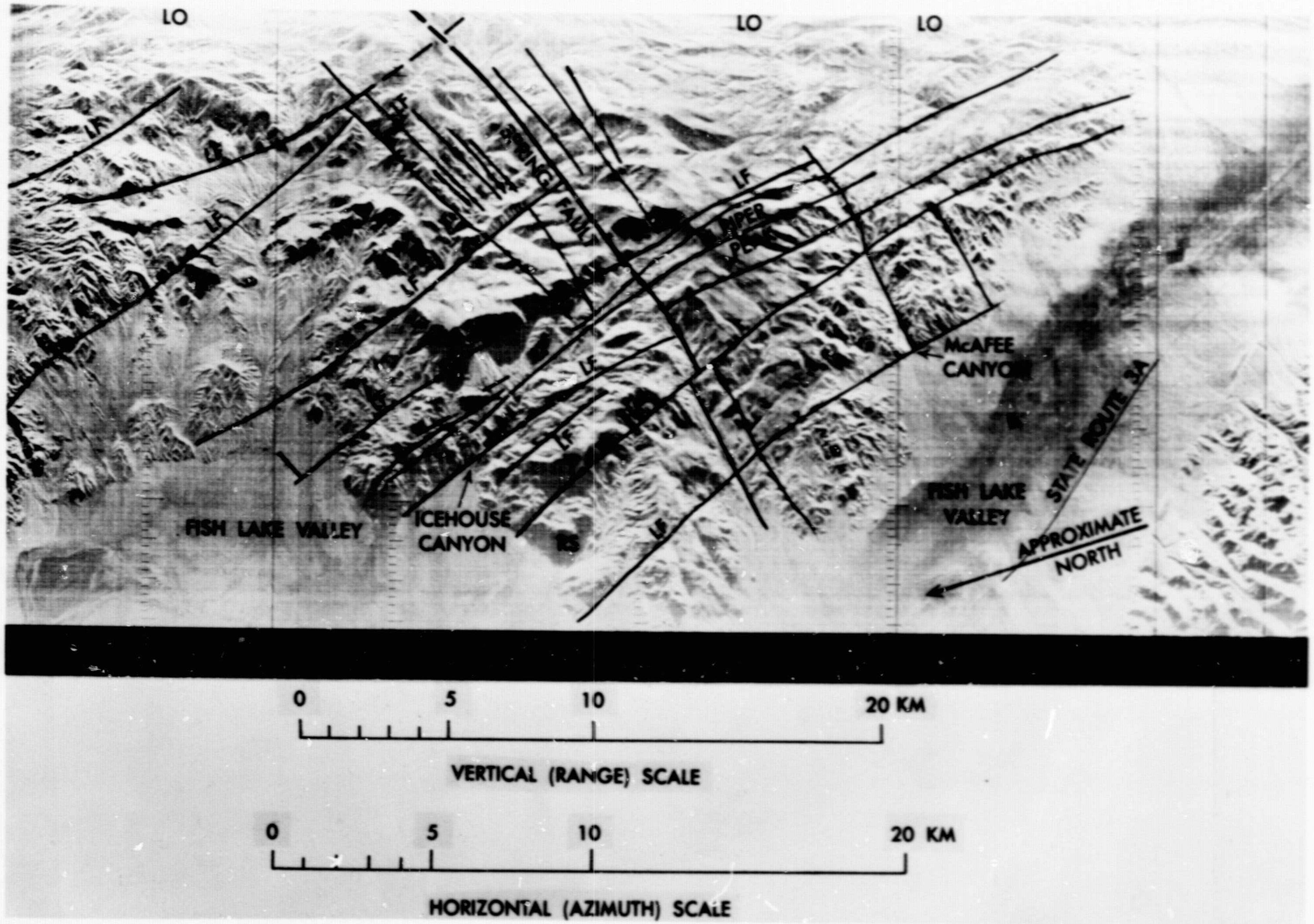

Figure 2B.: Sidelooking radar image of the Silver Peak Range-Fishlake Valley area, Esmeralda County, Nevada and Mono County, California. Cross polarized image, showing lineaments interpreted as possible faults, (LF) radar shadows (RS) and layover (LO).

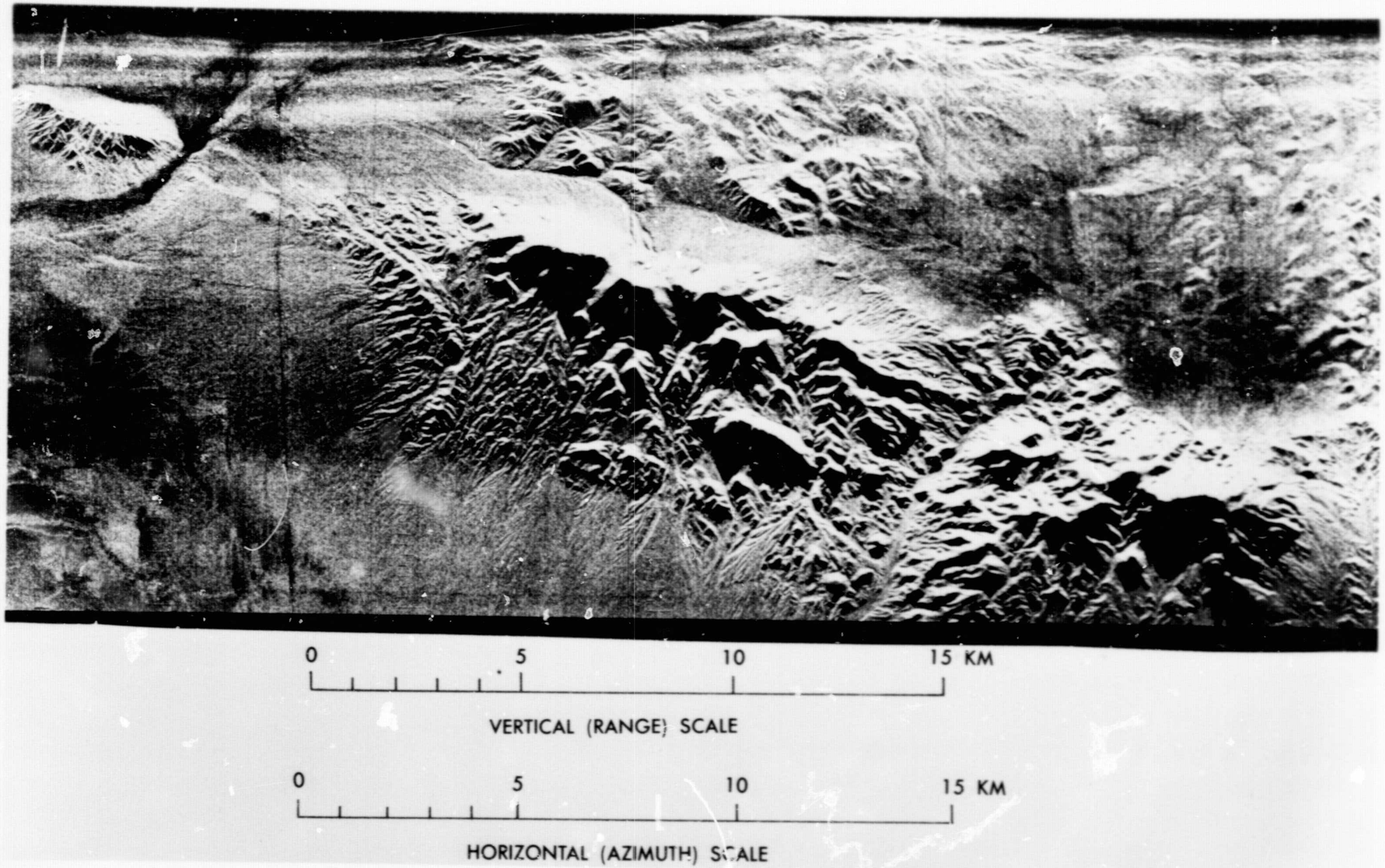

Figure 3A.: Sidelooking radar image of the Churchill Mt.-Fairview Peak-Slate Mountain-Monte Christo Mountains area, Churchill, Mineral and Nye Counties, Nevada. Like polarized image of the northern part of the area.

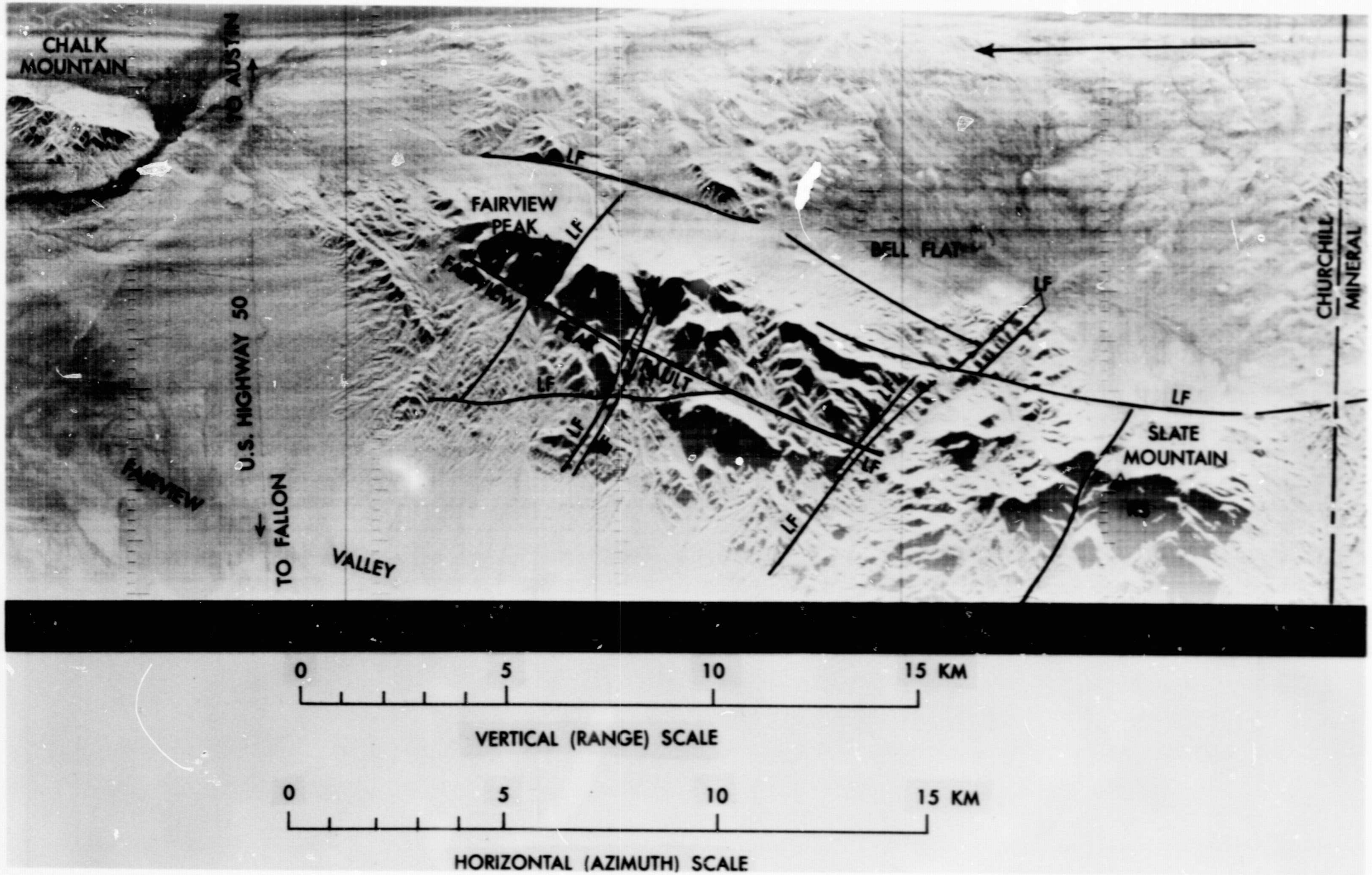

Figure 3B.: Sidelooking radar image of the Churchill Mt.-Fairview Peak-Slate Mountain-Monte Christo Mountains area, Churchill, Mineral and Nye Counties, Nevada. Cross polarized image of the northern part of the area, corresponding to "A," showing lineaments interpreted as possible faults (LF), radar shadows (RS), and layover (LO).

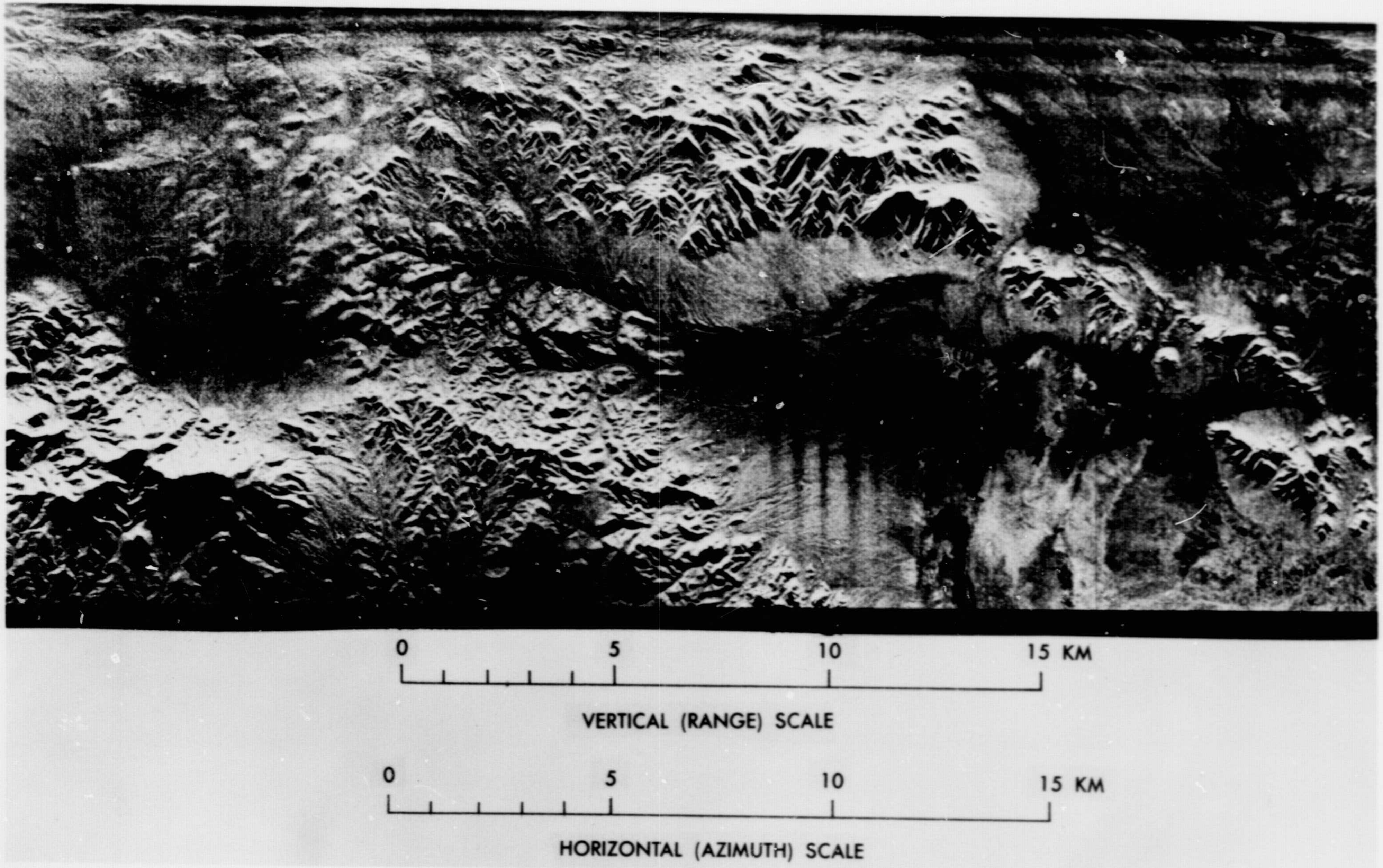

Figure 3C.: Sidelooking radar image of the **Churchill Mt.**-Fairview Peak-Slate Mountain-Monte Christo Mountains area, Churchill, Mineral and Nye Counties, Nevada. Like polarized image of the southern part of the area.

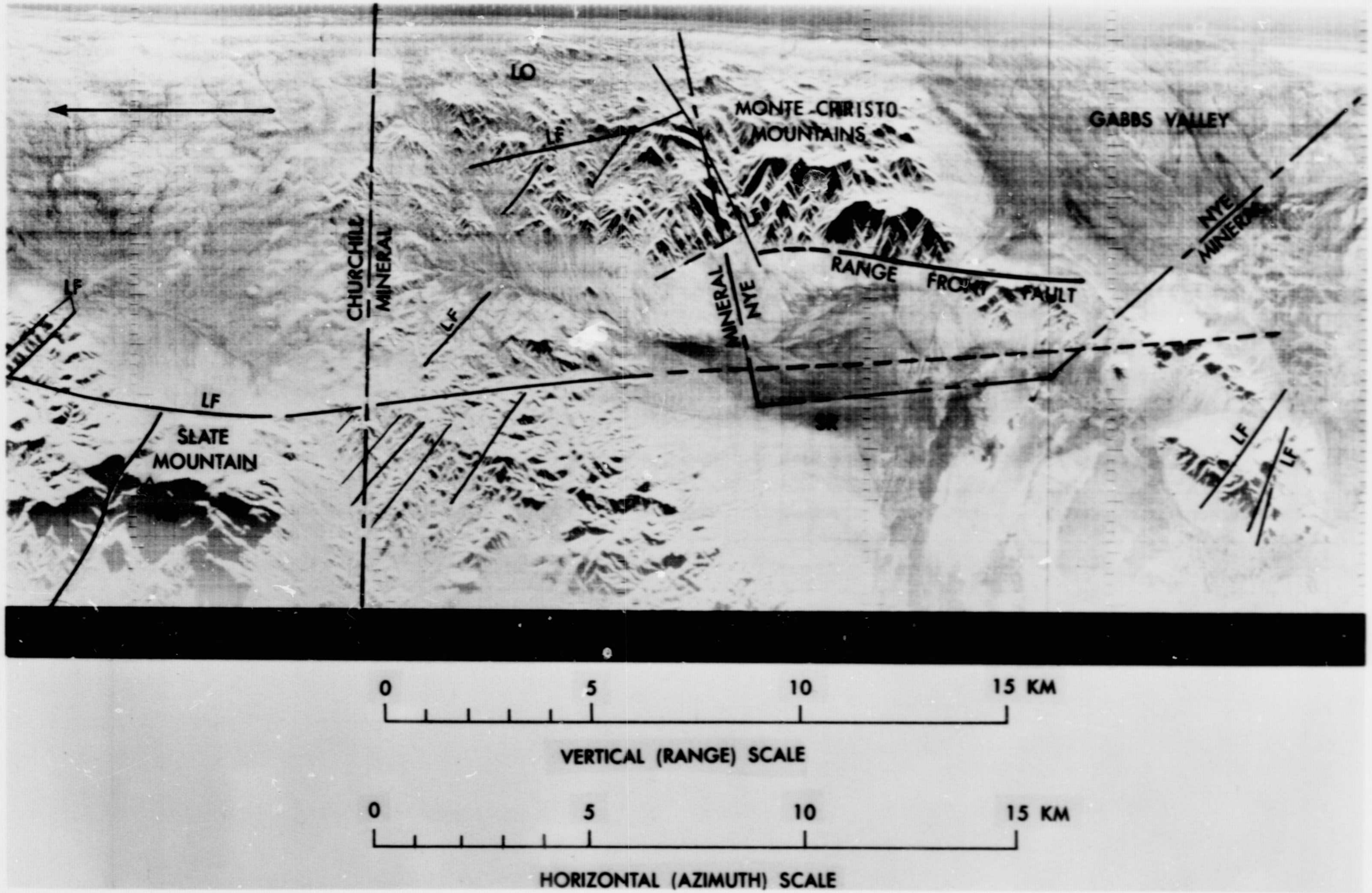

Figure 3D.: Sidelooking radar image of the **Churchill Mt.**-Fairview Peak-Slate Mountain-Monte Christo Mountains area, Churchill, Mineral and Nye Counties, Nevada. Cross polarized image of the southern part of the area, corresponding to C, showing lineaments interpreted as possible faults (LF), radar shadows (RS), and layover (LO).

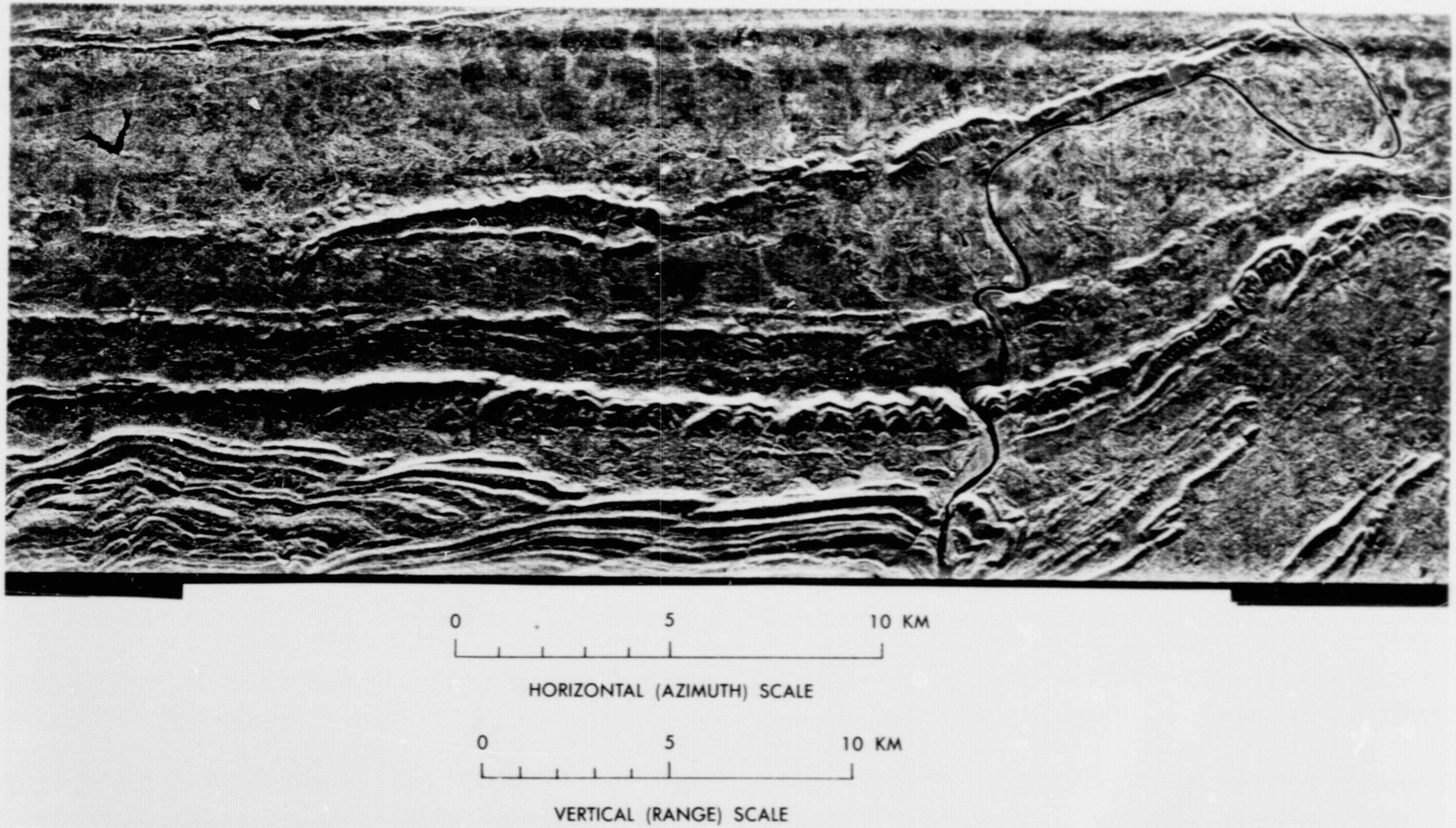

Figure 4A.: Sidelooking airborne radar image of the Coosa River Valley area south and southwest of Gadsden, Alabama. Like polarized image.

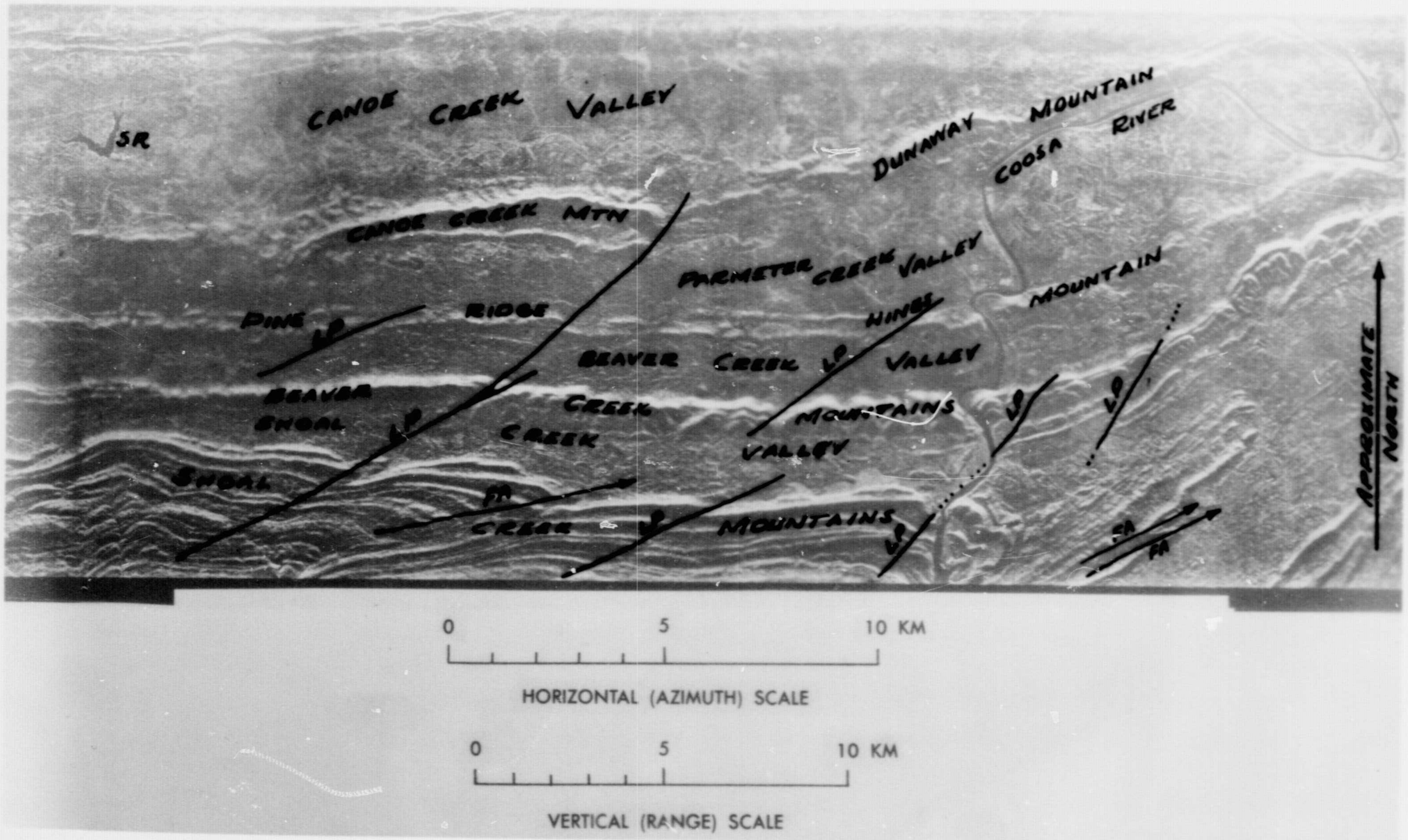

Figure 4B.: Sidelooking airborne radar image of the Coosa River Valley area south and southwest of Gadsden, Alabama, showing lineaments interpreted as possible faults, (LP), possible fold axis (FA), and specular reflection from water surface (SR).