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Supergene Uranium Deposits in Brecciated Zones of Laramide Upthrusts--Concepts and Applications

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Supergene Uranium Deposits in Brecciated Zones of Laramide Upthrusts--Concepts and Applications

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Abstract

Recent descriptions of uranium deposits at Copper Mountain, Wyoming, and the Pitch mine, Colorado, indicate important structural control by zones of crushed and brecciated rock along major Laramide uplift structures. The Copper Mountain deposits, especially the North Canning deposit, are in brecciated Precambrian rocks of the frontal lobe of the upper plate of the Owl Creek thrust. The frontal lobe contains antithetic faults caused by extension during arching of the upper thrust plate. Brecciated Leadville Dolomite in the footwall of the Chester fault zone is the most important control on uranium distribution at the Pitch mine. The Chester fault appears to be composed of several strands which together have a concave downward profile, steep at depth and flattening at the top, characteristic of upthrust faults or fold-thrust faults. A review of geologic observations and structural theory demonstrates that the structural permeability in these uranium deposits can be explained by brittle behavior in low pressure deformation characteristic of Laramide uplifts (termed forced folding and faulting). Dolomite, quartzite, granite, gneiss, and crystalline volcanic rocks behave as brittle materials which fracture rather than fold at depths less than about 6 km. When involved in upthrusts brittle rocks such as these develop abundant fractures and faults at two characteristic structural locations: (1) the frontal lobe of the upper plate, located high in the upthrust structure, as at Copper Mountain; and (2) the lower plate, particularly where folded or overturned below the upthrust, as at the Pitch mine. Fracturing of brittle upper plate rocks appears to be most intense where the upthrust arches as the dip of the fault plane decreases to less than 45°. Greatest fracturing in the lower plate appears to be deep in the upthrust structure where the fault dips about 65° and cuts a thick section (hundreds of meters) of brittle sedimentary rocks overlying the basement. These structural settings can create wide zones of fracturing and brecciation with geometry suitable for mass mining if mineralized and exposed near the surface.

Tuffaceous sedimentary rocks of middle Tertiary age fill basins adjacent to most Laramide uplifts and probably covered some fault zones. The tuffaceous sediments are considered by many to be the source of uranium for sandstone-type uranium deposits and probably are a viable source for structurally controlled supergene deposits. The volcanic rocks and uplift appear to be consequences of subduction of a lithospheric plate that caused increased heat flow and isostatic adjustment.

Targets for exploration or resource assessment can be predicted with the forced faulting concept using geologic maps of scales from 1:500,000 to 1:24,000. Application of this method to the Colorado Front Range suggests that the upper plate of the Williams Range and Elkhorn thrusts may be favorable for Copper Mountain-type deposits, and deformed Proterozoic rocks in the Sangre de Cristo Range might be favorable for Pitch mine-type deposits. Many Front Range uplifts involve thick sections of ductile Cretaceous shales which do not develop structural permeability and may seal structures in adjacent brittle rocks.

Introduction

Recent descriptions of uranium deposits at Copper Mountain, Wyoming (Yellich and others, 1978), and at the Pitch mine, Colorado (Ward, 1978; Nash, 1979) indicate that these deposits are contained within zones of crushed and brecciated rock along major Laramide[1] structures described as reverse or thrust faults. At a regional scale, away from the great complexities in the deposits, the faults appear to be curved in section, with near vertical dips at depth and flatter dips at higher structural levels. Interpretations of geometry and of the relative importance of compression or uplift in these faults vary greatly (see Berg, 1962; Osterwald, 1961; Prucha and others, 1965). Most observers agree, however, that the faults originate with block faulting in the basement and that deformation of overlying sedimentary rocks is reflected in a variety of fold and fault geometries. All physical features appear to be part of a shallow level tectonic environment called "forced folding" (Stearns, 1978). Where faults are produced in overlying sedimentary

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[1]Used in the sense of Tweto (1975) to cover the period of orogeny that occurred between Late Cretaceous and late Eocene time (about 72 to 40 m.y. ago).

rocks, the term "forced faulting" is appropriate. For geologists concerned with ore deposits, the importance of this environment is the creation of broad zones of structural permeability that are appropriate for epigenetic ore deposits, especially of uranium.

The purpose of this paper is to describe a tectonic environment that appears to be favorable for supergene uranium deposits. Recent descriptions of Laramide uplifts and associated thrusts, and new understanding of the mechanisms of forced folding and faulting, appear to permit a general prediction of the types of structural zones that should deform in a brittle manner. One attractive feature of this setting is that it appears favorable for wide zones of rock breakage that should be amenable to open pit mining, _if_ exposed near the surface and _if_ mineralized with more than about 0.05 percent uranium. The width of the mineralized crush zones at the Pitch mine and at Copper Mountain is an important factor in their reevaluation.

Structural Geology of Laramide Uplifts

A characteristic feature of the Rocky Mountains is uplifted blocks of Precambrian rocks, exposed in cores of mountain ranges, and adjacent deep basins filled by thousands of feet of Tertiary sediments. The geometry of the uplift structures has been heatedly debated with various authors advocating reverse fault block uplift, upthrust uplift, or fold-thrust upthrust (fig. 1; see reviews by Boos and Boos, 1957; Osterwald, 1961; Berg, 1962; Harms, 1964; Tweto, 1975; Stearns, 1978). In recent years many geologists have come to favor the view that the Laramide structures, and contemporaneous magmatism, are more consistent with vertical uplift than compressional thrusting and folding. However, it seems clear than no single style of deformation caused all structures; there is good evidence that following uplift, there was overturned folding and thrusting (see Berg, 1962), collapse on normal faults, and gravity sliding (Wise, 1963).

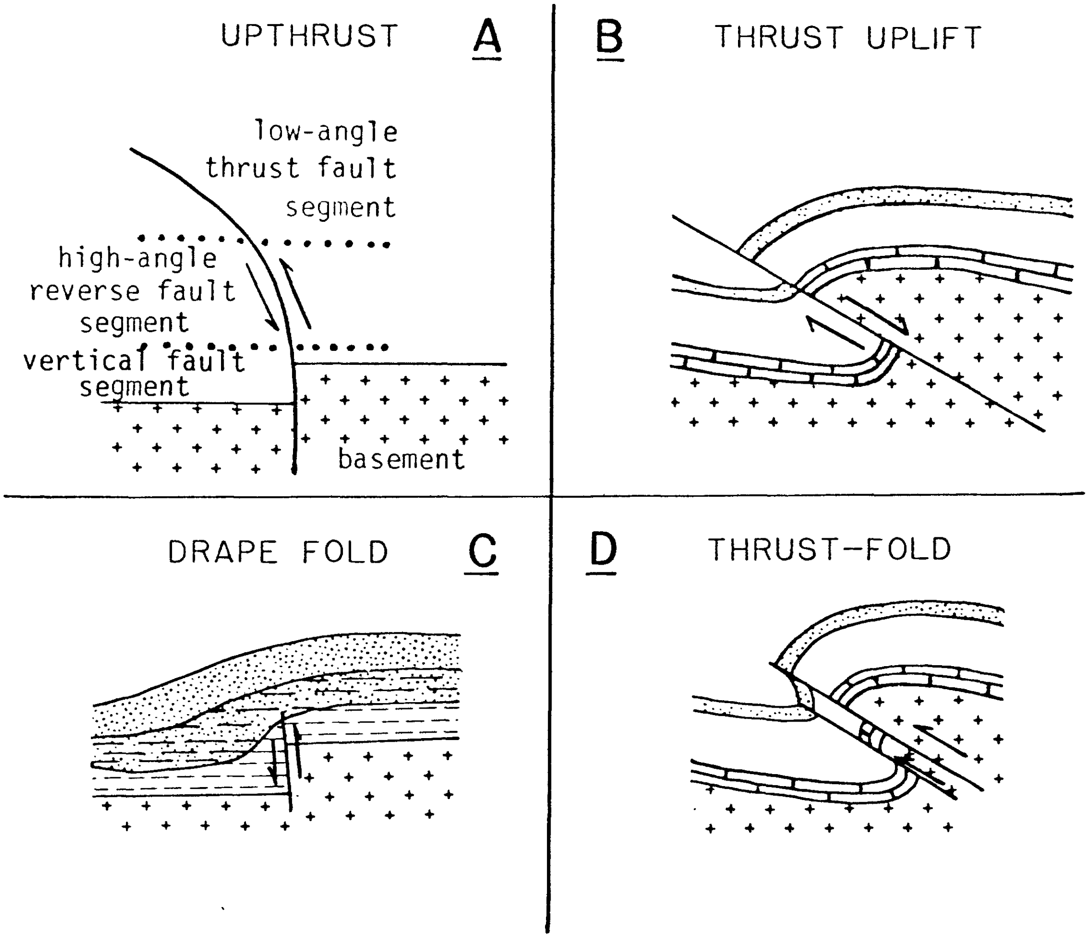

Figure 1.--Geometry and nomenclature of uplift structures.

- A Upthrust with characteristic concave downward profile (modified from Prucha and others, 1965).
- B Thrust uplift. Some have interpreted the fault plane to have a concave upward profile.
- C Drape fold in thin veneer of sedimentary rocks above basement fault.
- D Thrust fold with characteristic double fault and overturned syncline below thrust fault. (modified from Berg, 1962).

Observational and Theoretical Basis for Predicting Zones of Brittle Deformation

Field descriptions, experimental studies, and theoretical analyses are three means of predicting zones of brittle deformation suitable for uranium deposits. In the following discussion we will assume low-pressure conditions because numerous structural and stratigraphic studies indicate that sedimentary cover was not more than about 6 km thick in the Laramide uplifts under discussion. This depth converts to about 1,500 bars in a lithostatic system or 500 bars hydrostatic head.

Experimental studies.--Laboratory determinations of the ductility of some common rocks at low pressure and temperature (<1,500 bars, <200°C) are summarized in figure 2. Increased temperature and pressure makes most rocks more ductile, (Handin, 1966), making them more likely to bend or fold rather than fracture under stress. It is evident that, among sedimentary rocks, only dolomite or quartzite are brittle, whereas many varieties of plutonic, volcanic, and gneissic rocks are brittle. Crystalline basement rocks have brittle properties to a depth and temperature of about 18 km and 500°C according to experimental studies (Borg and Handin, 1966). Calculated stress distributions (Hafner, 1951; Sanford, 1959; Howard, 1966; Stearns and others, 1978; Couples and Stearns, 1978) indicate that differential uplift of rigid blocks induces a stress field in overlying rocks that is characterized by concave downward lines of maximum shearing stress that are positions of potential trough fault surfaces (fig. 3). Calculated shear trajectories match very well observed fault-plane attitudes, displacements, and rotation of rigid basement blocks. Scale models (see Sanford, 1959) and rock deformation studies (Friedman and others, 1976; Logan and others, 1978) likewise tend to confirm fold and fault patterns in layered rocks above uplifted basement blocks. Laboratory deformation of layered rock samples has demonstrated some of the following features: (1) Maximum deformation in the sediment layers occurs when the reverse fault angle in the forcing block (equivalent to basement) is about 65°. At steeper angles there is less deformation. With fault angles of 65° to 30° deformation in the downthrown block decreases, but extension fracturing in the upthrown block increases (Friedman and others, 1976). (2) Fault cross sections curve both upward and downward above basement faults with near vertical dip, but are only concave downward above faults which dip 65° or less (Logan and others, 1978). (3) Maximum faulting

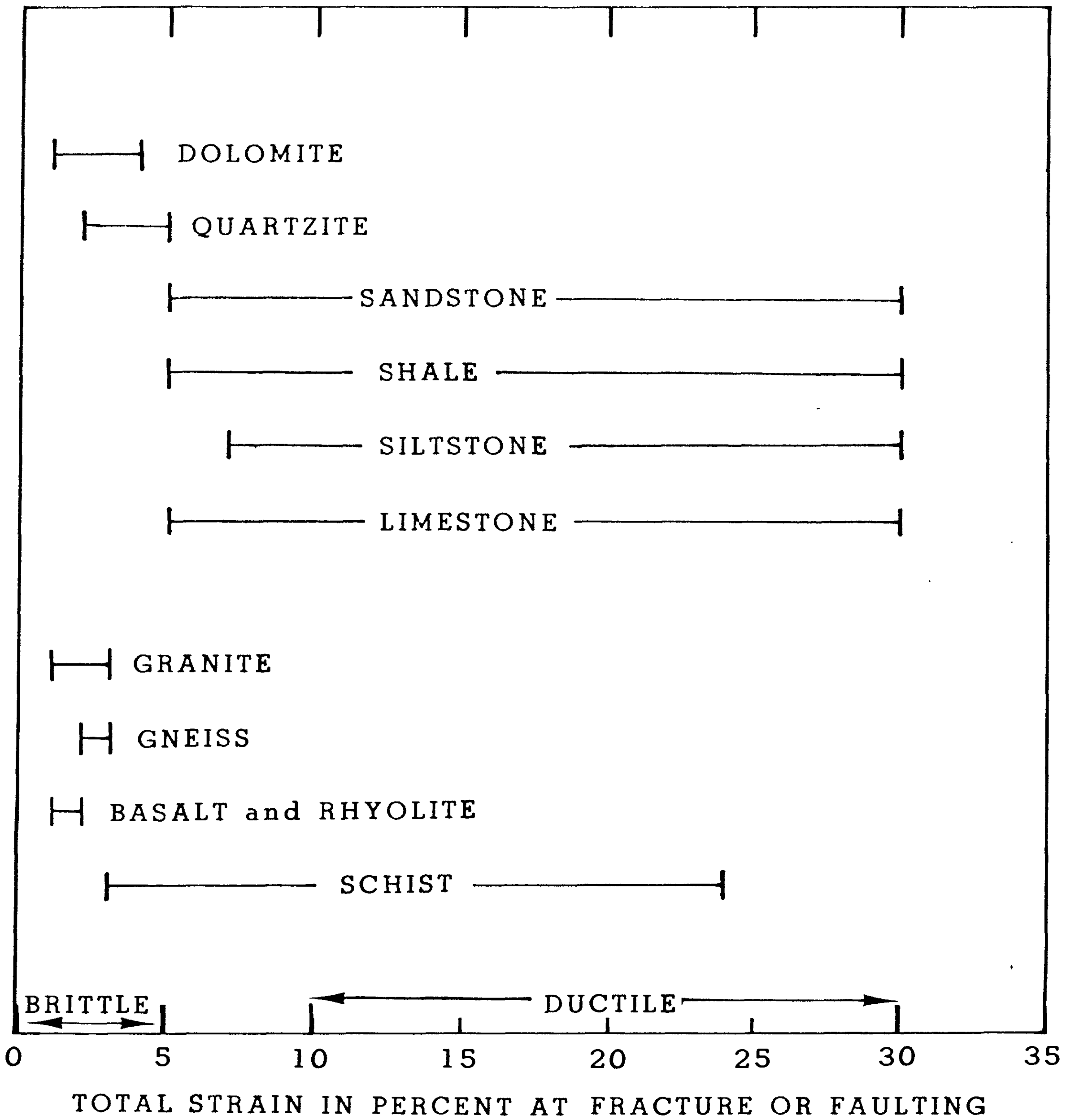

Figure 2.--Ductility of common rocks at low pressure (<1,500 bars) and low temperature (24° to 150°C). (Data from Handin, 1966.)

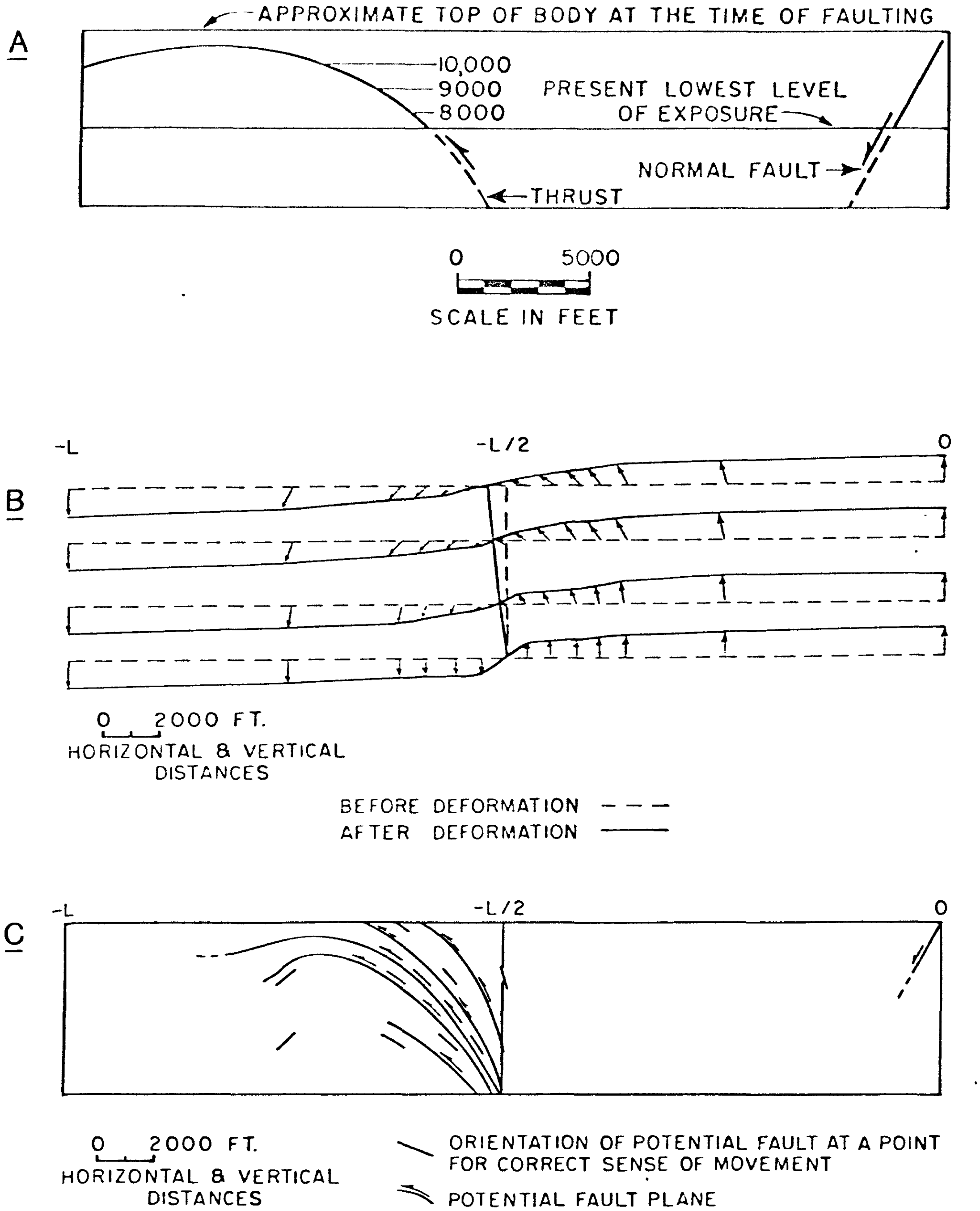

Figure 3.--Geometry and structural interpretations of Williams Range thrust (Modified from Howard, 1966). The scale of A, B, and C are the same.

A Idealized cross section derived from detailed mapping

B Displacement field in sedimentary section above vertical uplift of basement (forced fold)

C Calculated orientation of potential fault planes. Only fault planes with sense agreeing with Figure 3A are shown.

and fracturing occurs at fold hinges where the rate of change of dip is greatest (Friedman and others, 1976) (fig. 4). (4) Increased displacement of the forcing block causes the locus of deformation to move from the lowest bed toward the upthrown block (fig. 5). Faults tend to be initiated in the lowest block, and displacements progress toward upper levels of the upthrown block.

Field relations.--Geometry of faults and folds related to Laramide basement uplift has been described and discussed in numerous publications, some mentioned previously. Complex geology with rapid changes in bedding and fault attitudes makes accurate three dimensional interpretation difficult. Drilling and seismic data have provided some additional control, but the details of geology are rarely known. Drilling at spacings as close as about 10 m in uranium exploration and development, as at the Pitch mine (Nash, 1979) and at Copper Mountain (Yellich and others, 1978), demonstrate great complexity. Indeed, relationships at a scale of 1:600 are often too complex to permit understanding of regional problems. Despite gaps in information, published accounts of regional structures show many features observed at the uranium deposits. Two types of deformation involving hanging wall and footwall zones will be reviewed as especially pertinent to our problem.

Sequential development of fold-thrusts during Laramide uplift was proposed by Berg (1962). This type of deformation produces great deformation, including folding, in the lower plate, and probably occurred in the Pitch mine area. According to Berg the first stage (fig. 6) was predominantly vertical uplift. Continued uplift produced gentle folding in the downdropped block. Finally, compression became dominant in some areas and the sedimentary rocks were overturned and deformed by thrusts. According to the experimental data reviewed previously, any brittle sedimentary rocks (dolomite, quartzite) in the overturned fold of the downdropped block should be extensively fractured.

Abundant faulting is observed in the uplift block of the Owl Creek Mountains, Wyoming, an especially well studied uplift (see Tourtelot, 1953; Wise, 1963; Ferris, 1968; Keefer, 1970). The major frontal fault, the South Owl Creek Mountains fault, does not crop out but is interpreted from drill-hole data to dip about 45^{o} north (Keefer, 1970). The uplifted block is well exposed and some interesting features are described by Wise (1963; fig. 7). The uplifted block contains numerous normal faults, the most obvious visible

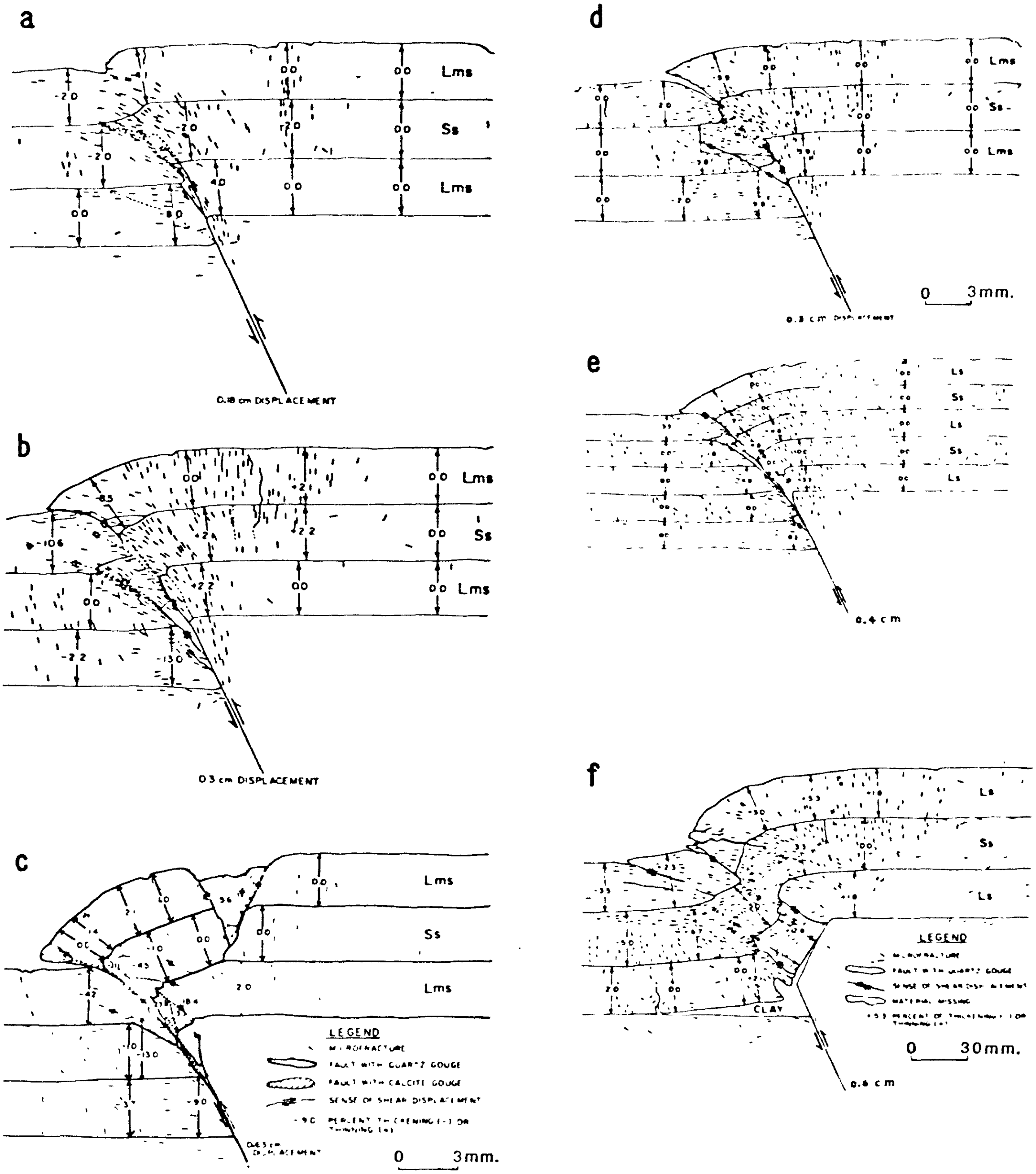

Figure 4.--Fault and fracture patterns in experimentally deformed layered rocks (modified from Friedman and others, 1976). Figures are sketches of thin sections cut across deformed samples. In these experiments sandstone (Ss) is a brittle material and limestone (Lms) is ductile. These experiments were conducted at 1.0 kilobar confining pressure. The fault angle in forcing block is 65° in all cases.

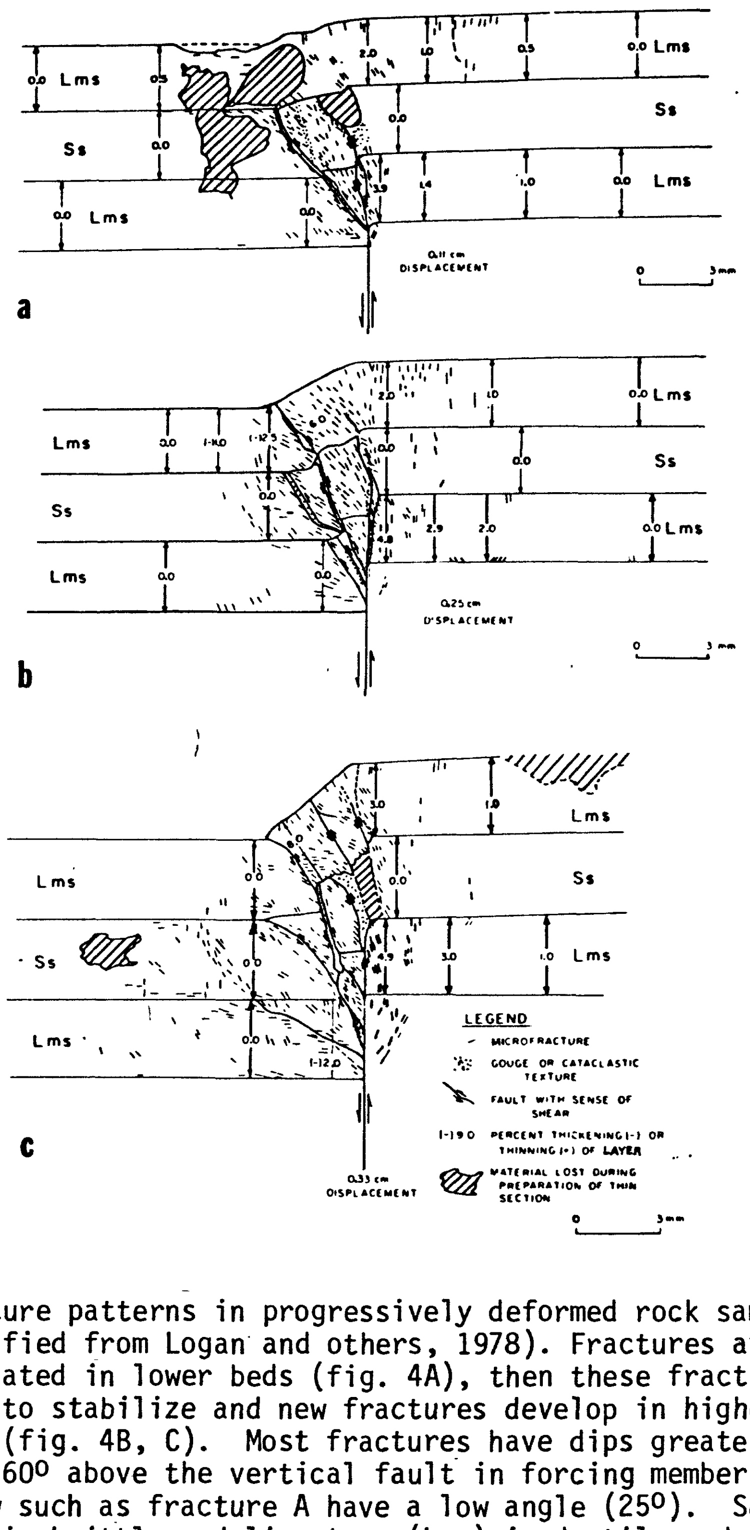

Figure 5.--Fracture patterns in progressively deformed rock samples (modified from Logan and others, 1978). Fractures are initiated in lower beds (fig. 4A), then these fractures tend to stabilize and new fractures develop in higher beds (fig. 4B, C). Most fractures have dips greater than 60° above the vertical fault in forcing member, but a few such as fracture A have a low angle (25°). Sandstone (Ss) is brittle and limestone (Lms) is ductile under conditions of experiment.

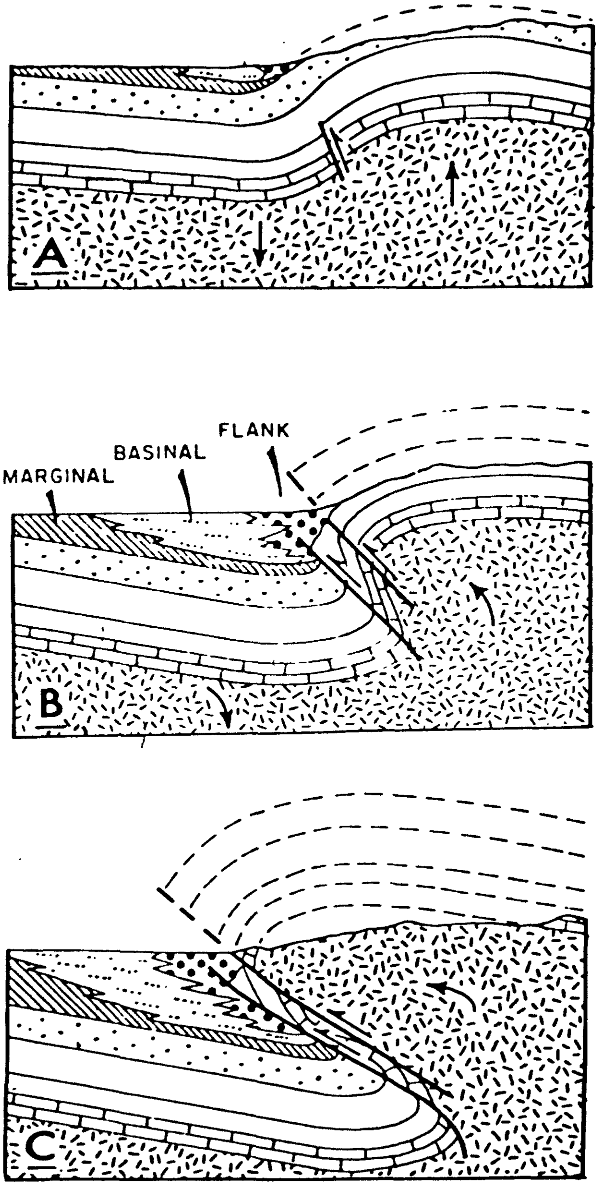

Figure 6.--Diagrams illustrating sequence of uplift, faulting, and folding according to Berg (1962).

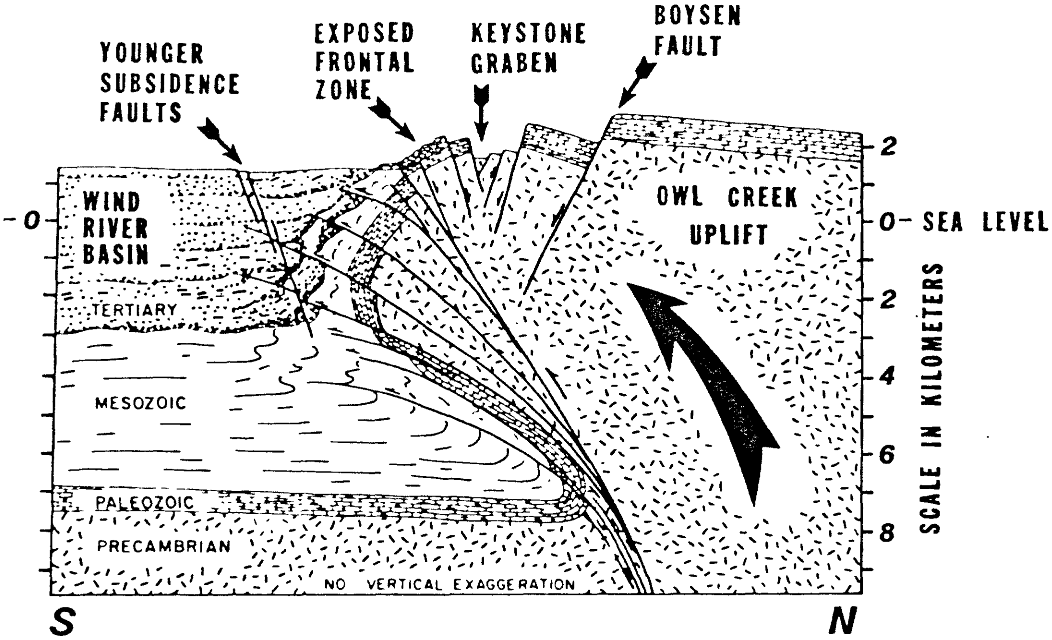

Figure 7.--Interpretation of structure of frontal zone of Owl Creek uplift, Wyoming (modified from Wise, 1963).

structural features in the area. Together these faults create grabens, horsts, and tilted basement blocks. The Boysen fault, the largest of the subsidiary normal faults, marks the northern limit of this style of faulting above the main upthrust. Wise (1963) interprets the "keystone graben" blocks to have formed as the result of basement arching and extension in the frontal lobe above the curving upthrust fault. (Note that virtually identical features have been produced experimentally; fig. 4C). Associated with rotated normal fault blocks at the frontal zone are gravity slides that broke away from the uplift block. Movement continued along faults in the frontal zone, forming grabens that influenced deposition and erosion of the lower Eocene Wind River Formation and the overlying middle Eocene Tepee Trail Formation (Ferris, 1968). Sandstone in these Eocene formations contains uranium deposits at several localities in the Copper Mountain area (Yellich and others, 1978).

In summarizing the theoretical and observational data on behavior of rocks in Laramide block uplifts, Stearns (1978) emphasized the roles of pressure, ductility, stratigraphic layering, and degree of attachment to the basement. The first two parameters have been mentioned earlier. Degree of attachment to the basement, termed "welding" by Stearns (1978), determines the amount of slip along the basement contact, which makes folding possible. Stearns (1978) discusses three situations for forced folding and faulting: (1) Unattached, brittle sections: folding occurs because beds can slip on the forcing member, and a few reverse faults develop in the sedimentary veneer. The brittle member is rigid and limits folding, hence structural blocks are created (fig. 8A). In this configuration faults develop only at block boundaries. This is probably not a favorable geometry for production of structural permeability. (2) Attached, brittle sections: many local faults develop because the sedimentary veneer can not slip along the uplifting block. Numerous faults occur in the regions of anticlinal and synclinal hinges (fig. 8B) as described in the section on experimental observations (fig. 4). With progressive uplift, the hinge migrates, causing fractures to develop in many places, rather than only at a few block boundaries as in case no. 1. This appears to be the best configuration for development of structural permeability in the sedimentary veneer. (3) Attached, ductile sections: Drape folds develop in this situation because the ductile beds thin rather than fault. There is strong intergranular cataclasis within the

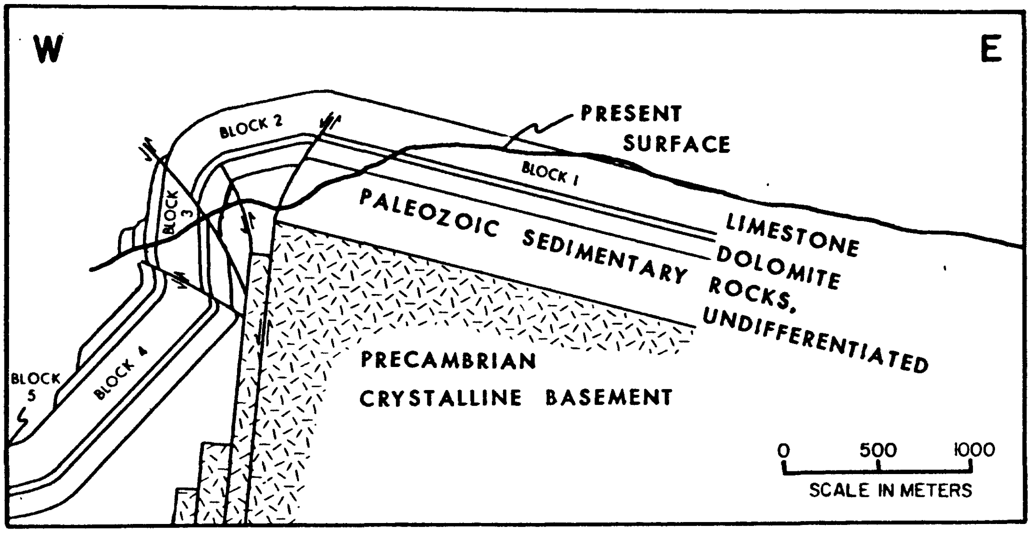

Figure 8A.-- Cross section of Rattlesnake Mountain west of Cody, Wyoming showing structural blocks created in forced folding (modified from Stearns, 1978).

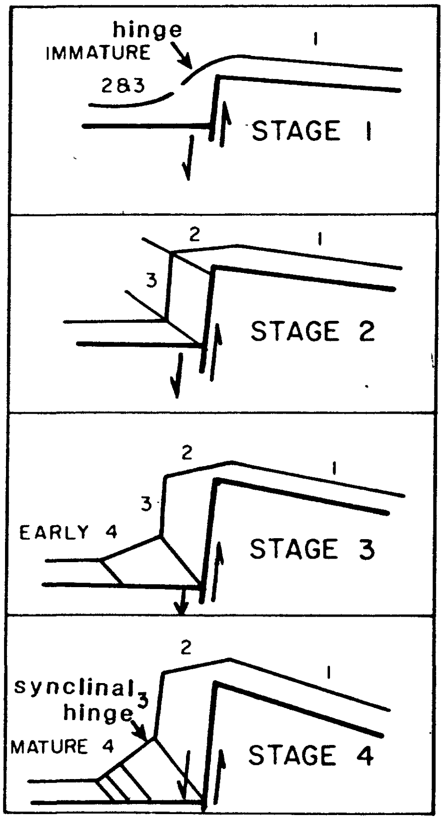

Figure 8B.--Interpreted sequence of block development during forced folding (Stearns, 1978) Stage 1, basement uplift causes drape folding in overlying sedimentary veneer; stage 2, faults are created at the boundaries of block 3 to allow it to rotate toward basement fault; the hinge in block 2 is fixed; stage 3, block 3 cannot move horizontally and continued displacement causes faulting at the synclinal hinge, creating block 4;and stage 4, additional displacement produces more faulting in the synclinal hinge area of block 4.

Figure 8.--Cross sections illustrating sequence of structural development during forced folding (modified from Stearns, 1978).

thinned beds, but the lack of faulting limits permeability in the beds. Thus this mechanism is probably not suitable for the creation of permeability for ore deposits.

A variant of case no. 3 is described by Cook (1978) in which a brittle quartzite is contained within ductile sediments (fig. 9). The ductile beds slip and thin, and the brittle bed is fractured (and thinned) as it is stretched above the reverse fault developing in the basement. According to Cook (1978) the intense fracturing created high permeability suitable for petroleum migration and trapping, and thus this situation might be favorable for the development of uranium deposits.

An obvious complicating factor in all of these situations is the presence of ductile beds (especially shale) adjacent to brittle beds that fracture and fault. There are numerous reports of ductile beds being squeezed into faults, and of low permeability along faults where one or both walls are ductile rocks. Hence there are several configurations in which ductile beds can be expected to seal off the structural permeability created in brittle zones. This will be considered further in a later section.

Structural Controls of Uranium Along the Chester and Owl Creek Fault Zones

With the preceding discussion of structural and mechanical properties in mind, let us review the structures that contain uranium deposits in two upthrust fault zones. Much of the following is highly speculative and subject to alternative interpretations.

Marshall Pass District.--The Pitch, Little Indian, and Lookout 22 uranium deposits of the Marshall Pass district are located about 60 km east of Gunnison, Colorado (Malan, 1959; Ward, 1978; Nash, 1979; Olson, 1979). The Pitch and Little Indian mines occur along the Chester fault zone, which places Precambrian rocks above and west of rocks of Paleozoic age (fig. 10). The Lookout 22 deposits are found in faults in Precambrian rocks about 2 km east of the Chester fault. The Chester fault is believed to be of Laramide age because similar faults about 30 km to the west displace Cretaceous rocks. The Chester fault does not appear to cut Oligocene(?) volcanic rocks (Olson, 1979), although volcanic rocks are locally turned on end adjacent to the fault, perhaps reflecting renewed movement. The Chester fault is well exposed

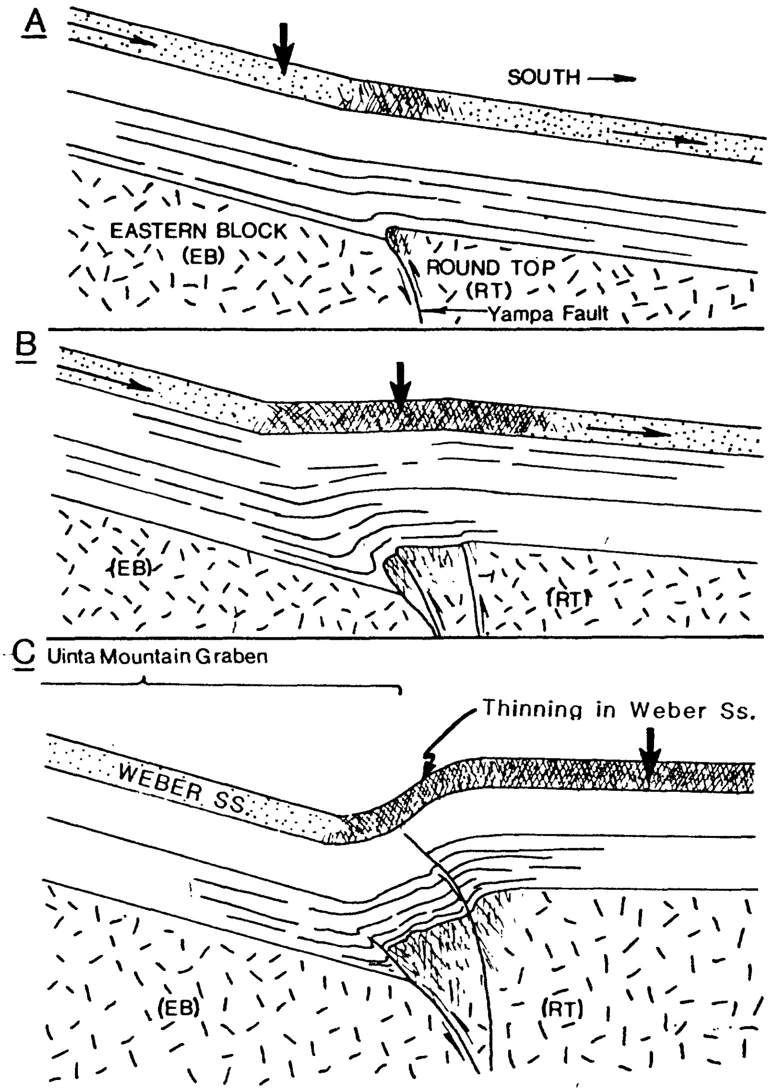

Figure 9.--Development of fracture permeability in brittle quartzite above ductile rocks in forced fold (modified from Cook, 1978). Arrow marks reference point of southward movement of Weber Sandstone.

A Uplift of basement on reverse fault starts forced fold

B Continued displacement causes slippage and thinning in ductile beds, but brittle quartzite cannot thin. Quartzite fractures as it is bent over the fold hinge

C Upthrust continues but north end of Weber Sandstone is stationary, causing tensile stress and thinning of fractured quartzite at only one locality near the old townsite of Chester where the fault dips 60° eastward. Drilling at the Pitch mine indicates the fault there has an average dip of 70° east. Surface mapping in the area is hampered by recent downslope wash of Precambrian rock and by Tertiary colluvium, but several features of interest should be mentioned with reference to figure 10. (1) The Chester fault typically has a dip of about 60° to 70° east. In the Pitch mine major east and west strands are known to occur about 100 m apart with numerous faults in between (fig. 10, 1A). On the ridge north of the Pitch mine (fig. 10, 1B) the trace of the fault swings to the west; this is probably the highest structural level of the fault. The geometry of the fault trace suggests this portion of the fault has a more gentle dip, possibly 45° or less. South of the Pitch mine (fig. 10, 1C) a thin slice of Precambrian rocks extends westward over Paleozoic rocks, apparently a thrust slice that moved west of the main fault zone; the timing of this westward thrusting is not known. (2) The footwall of the Chester fault zone consists of rocks of Cambrian to Pennsylvanian ages. The lower 330 m of the section is dolomite and quartzite (brittle), and the upper part of the section consists of about 300 m of shale, siltstone, sandstone, and limestone (ductile). These rocks are in an overturned syncline in the 500 m interval west of the Chester fault zone (fig. 11). (3) East-trending faults cut the syncline and Chester fault zone (fig. 10, 3), forming a series of horst and graben blocks that have rotated slightly around east-trending axes. These probably can be called tear faults and probably formed late in the movement history of the Chester fault zone. Their geometry is not sufficiently well known to judge whether they formed on E-W compression or on relaxation. (4) North-trending faults with probable normal displacement occur in the footwall block and may represent late stage subsidence faulting as described by Wise (1963; fig. 6). Some of the complex high angle offsets within the Chester fault zone might also represent late-stage subsidence upon relaxation, but the timing and absolute sense of movement cannot be determined within this complex zone of faulting. (5) Precambrian rocks forming the uplift block do not readily display faults, but some, as at the Lookout 22 mines (fig. 10, 5A), may represent normal faults produced during arching of the upthrust block. However, no keystone graben can be discerned. Some faults further east (fig. 10, 5B) offset Oligocene(?) volcanics, and may have formed during late stage relaxation, or the offsets of volcanic rocks may indicate reactivation of older faults.

In summary, the Chester fault zone displays many of the features expected

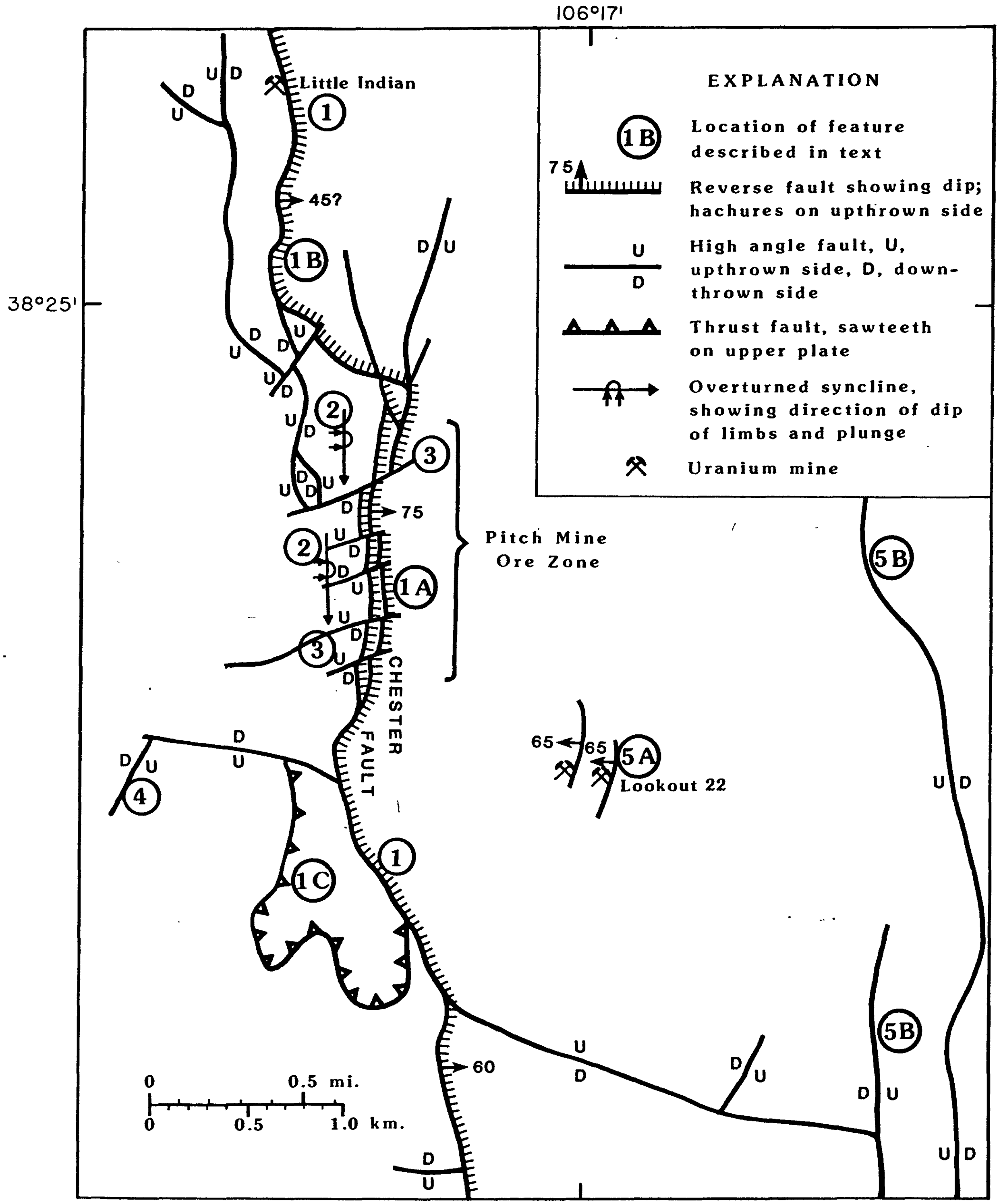

Figure 10.--Simplified map of structural features in Marshall Pass district, Colorado (modified from Olsen, 1979; Nash, 1979).

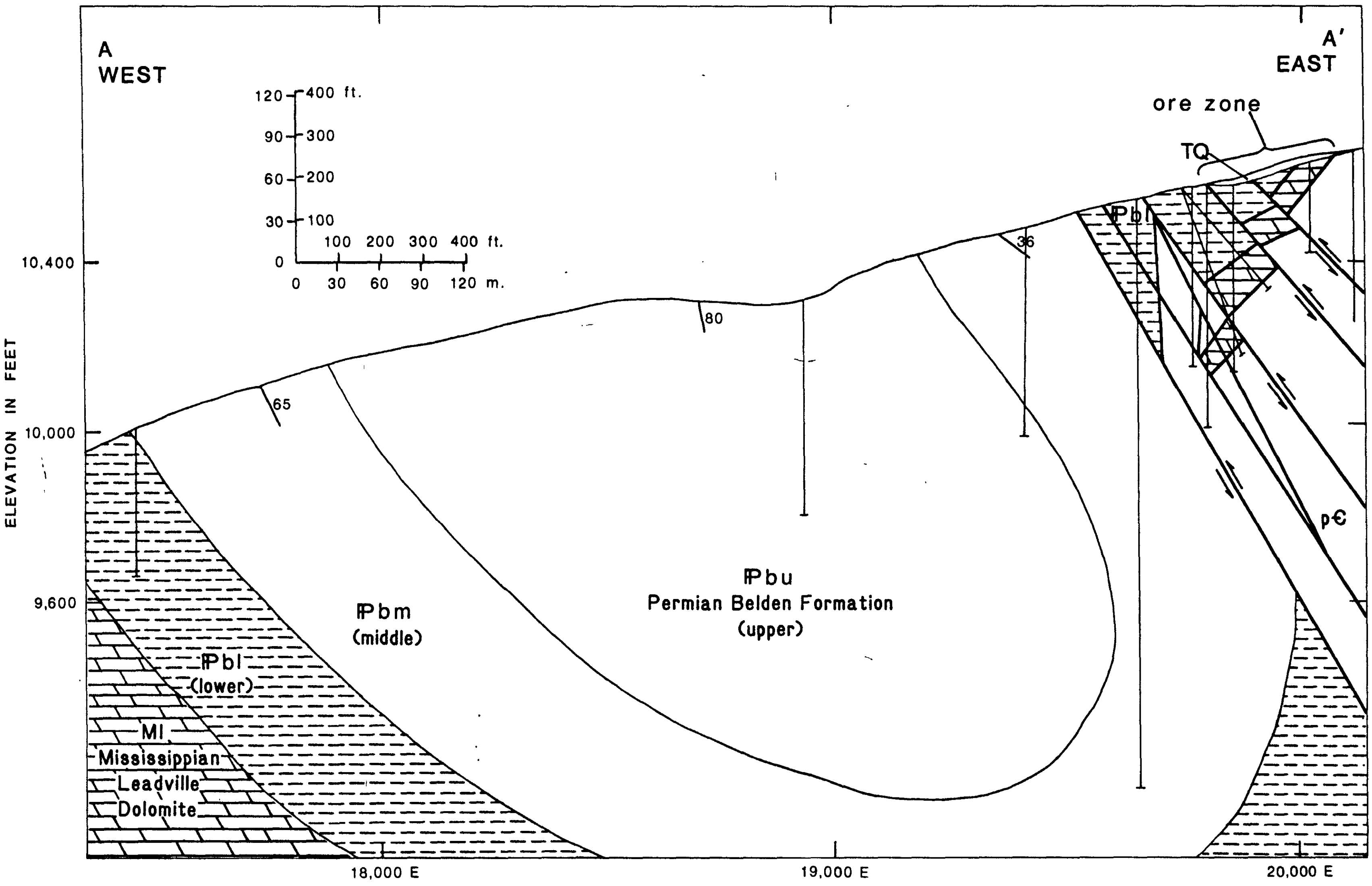

Figure 11.--Cross section of Chester upthrust in the Pitch Mine area.

in basement uplifts that cause forced folding and faulting. The geology is that of Stearns' attached, brittle case no. 2 (1978). The predicted abundant faulting and fracturing is present and is a key ore control at the Pitch mine (Nash, 1979). At the Little Indian mine uranium is hosted by a quartzite that has been turned on end and brecciated in the Chester fault zone (Malan, 1959; Olson, 1979). The overturned syncline and probable renewed movement on several faults appear to be consistent with Berg's (1962) hypothesis of sequential development of fold-thrusts (fig. 6) and the fracturing of brittle rocks that it predicts. Finally, the Lookout 22 deposits occur in Precambrian rocks in faults that may have been produced by arching of the uplifted block.

Copper Mountain district.--Copper Mountain is in the Owl Creek Mountains of north-central Wyoming. Precambrian granitic and metasedimentary rocks form the northern upthrust block mentioned earlier (fig. 7). The Wind River Basin south of the upthrust contains a thick section of Tertiary sediments with abundant volcanic material (fig. 12). The Tertiary rocks cover the main Owl Creek reverse/thrust fault zone (Keefer, 1970); the projected location of thrusts is shown in figure 12. Numerous uranium deposits occur in the Precambrian and Tertiary rocks, some of which were in production in the period 1955-1970. Total production from the district has been about 500,000 pounds U_3O_8 (Yellich, and others, 1978). The most promising deposit in the district appears to be the North Canning deposit, which is being drilled and evaluated by Rocky Mountain Energy Company as a medium grade, large volume deposit with potential for open pit mining (Yellich and others, 1978). Detailed studies (Yellich and others, 1978) demonstrate great structural complexity in shattered granitic rocks which is not evident at the surface due to a thin cover of Tertiary sediments. Uranium values greater than 0.02 percent U_3O_8 are in the hanging wall of the North Canning reverse fault, which dips about 60° south, often in crush zones with more than 65 fractures per meter. Numerous subsidiary high angle normal and reverse faults were found in the mineralized zone. The faulting is similar to that described by Wise (1963; fig. 6) in the Owl Creek uplift 20 km to the west.

The structural setting (figs. 12, 13) of the North Canning deposit is the upper plate where brittle granitic rocks fractured in response to the tensile stress of arching during upthrust movement. This structural behavior is noted in experimental studies previously reviewed (fig. 4). Collapse of the leading

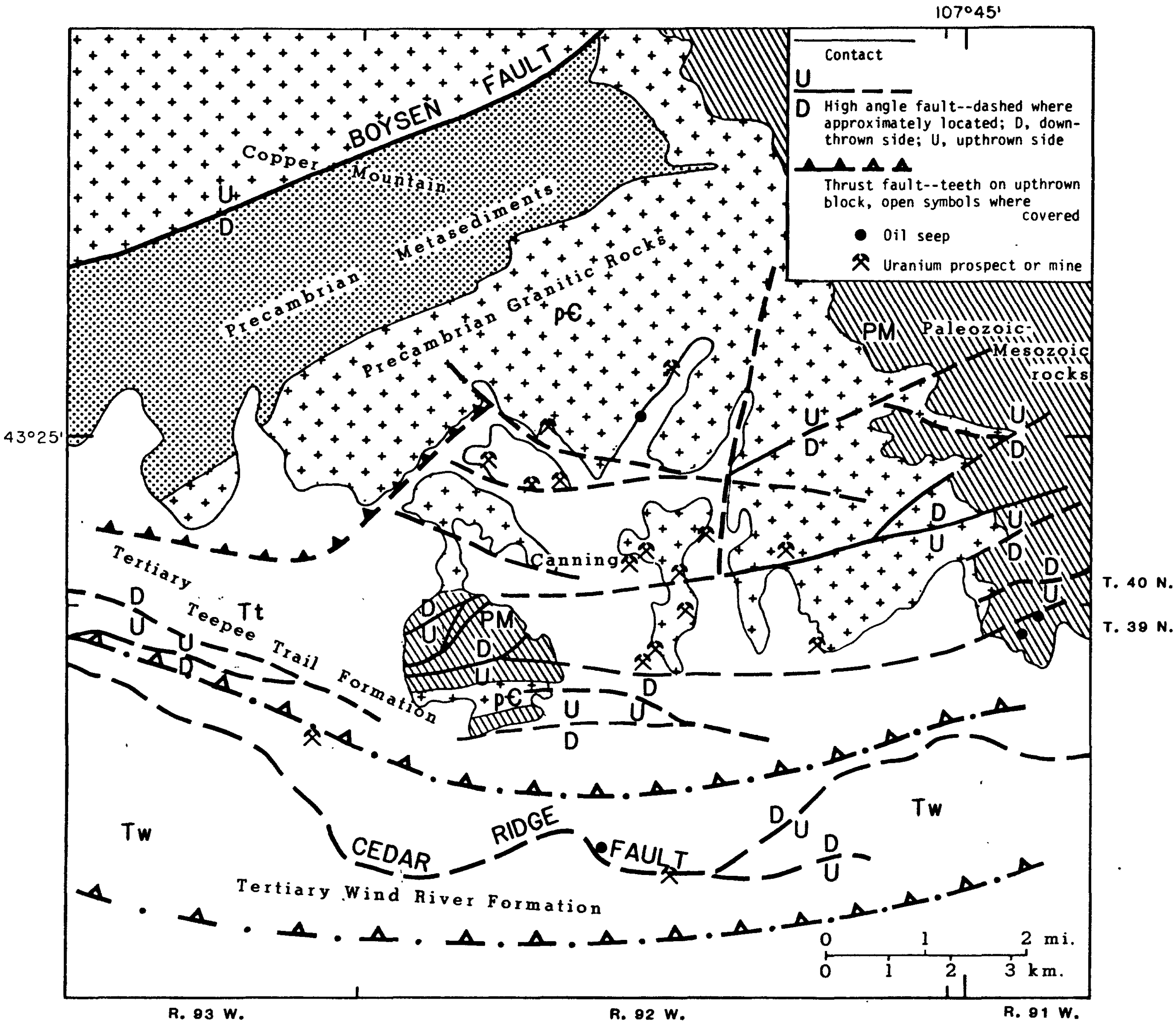

Figure 12.--Generalized geologic map of the Copper Mountain district, Wyoming (modified from Tourtelot, 1953; Yellich and others, 1978).

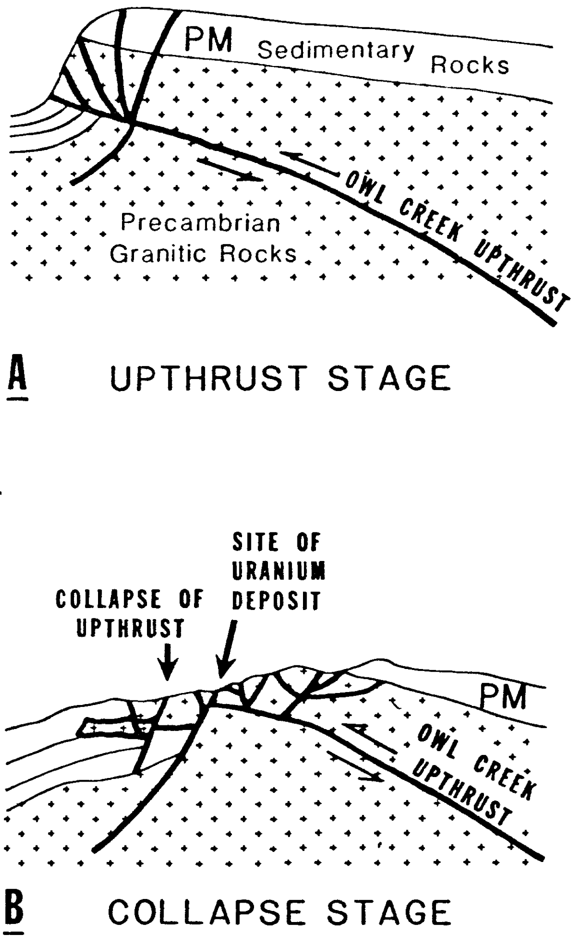

Figure 13.--Interpretive cross section of the Owl Creek uplift at Copper Mountain showing development of North Canning deposit (modified from Yellich and others, 1978). A, upthrust stage and B, collapse stage.

edge of the upper plate also contributed to faulting and shattering (fig. 13). Yellich and others (1978) describe a supergene genesis of several stages with final deposition occurring at sites of mixing of descending uranium-bearing solutions and upwelling, basin-derived brine carrying hydrocarbons. Source of uranium could be either fractured, accessible granitic rock or overlying Tertiary volcanic-rich sediments.

Laramide Orogeny, Magmatism, and Plate Tectonics

Many geologists have discussed the association and timing of orogeny and magmatism, and in recent years plate-tectonic models have been proposed. To the author there seems to be a recurring pattern of volcanism or volcaniclastic rocks over or adjacent to Laramide uplifts as pointed out by several authors (see Tweto, 1975; Izett, 1975; Steven, 1975; and Epis and others, 1976). Most of the volcanic activity was Paleocene to Eocene, and postdated initial uplift, although deformation of mid-Tertiary formations has been cited as evidence of renewed uplift or a shift from uplift to thrusting. These observations are consistent with Gilluly's (1973) observation that orogeny and magmatism are episodic and often not simiultaneous. The association of volcanic rocks with zones of Laramide uplift is of interest because mid-Tertiary tuffaceous sediments are often cited as likely sources for sandstone-type deposits in Tertiary basins of Colorado and Wyoming. The empirical association of uranium deposits with tuffaceous rocks suggests that a similar source mechanism could work for supergene "vein-type" deposits such as in the Marshall Pass and Copper Mountains districts where tuffaceous rocks overlay fault zones.

Plate-tectonic models have been proposed to explain Laramide uplift or magmatism (Lipman and others, 1971; Lipman and others, 1972; Lowell, 1974; Coney, 1976; Woodward, 1976; Dickinson and Snyder, 1978). Several authors agree that the Pacific Ocean plates were subducted at an unusually low angle of about 20 degrees as proposed by Lipman and others (1971). Models that explain reasons for tangential compression (Coney, 1976; Dickinson and Snyder 1978) do not appear to explain uplift. Petrochemical arguments (Lipman and others, 1971; 1972) are attractive and suggest underthrusting of an oceanic plate as far as the Rocky Mountains and a mechanism for Laramide magmatism. The subducted plate might have provided the buoyancy to cause uplift (Lowell, 1974), or the buoyancy might be explained by phase changes in the mantle or upper crust (Woodward, 1976) or flowage of sialic material in the lower crust (Gilluly, 1973). In a general manner, it may be possible to relate uplift and magmatism to plate tectonic movement that lead to isostatic adjustment and increased heat flow.

Application of Structural Model

The point of the previous review and discussion is to develop a structural model that can predict exploration targets and aid resource assessment. Application of the model appears to be possible using geologic maps at scales from from 1:24,000 to 1:250,000. Here the model is applied to the Rocky Mountains of Colorado within the Greeley, Denver, and Pueblo $1^{o}x2^{o}$ quadrangles (scale 1:250,000) for which the USGS is currently assessing uranium favorability as part of the National Uranium Resource Evaluation (NURE) program of the U.S. Department of Energy.

To recapitulate, the following features would be sought using the structural model. First, look for basement uplifts. Second, examine maps for reverse and thrust faults. Third, check for brittle rocks involved in the upthrusts, particularly in the arched zone of the upthrust (hanging wall) block (for Copper Mountain type deposits) or in the downdropped (footwall) block. Folded sedimentary sections containing thick brittle units, particularly when overlying the basement, are a particularly good target for Pitch-type deposits. Fourth, evidence for possible associated features such as adjacent (formerly overlying?) volcanic sediments and oil seeps should also be compiled.

Inspecting the small scale maps of the Front Range, some interesting possibilities are apparent. From north to south they are (fig. 14): (1) the northeastern flash of the Front Range near Fort Collins; (2) the western range front in the Never Summer Mountains-Cameron Pass area; (3) the Stillwater thrust fault north of Granby; (4) the Williams Range thrust near Dillon; (5) the Elkhorn thrust in South Park; and (6) the thrusts in the Sangre de Cristo Range. Let us start the discussion with some of the uplifts that are well described in the literature.

Williams Range thrust.--This is a classic and much described structure (see Lovering, 1935; Wahlstrom and Hornbach, 1962; Howard, 1966) that places

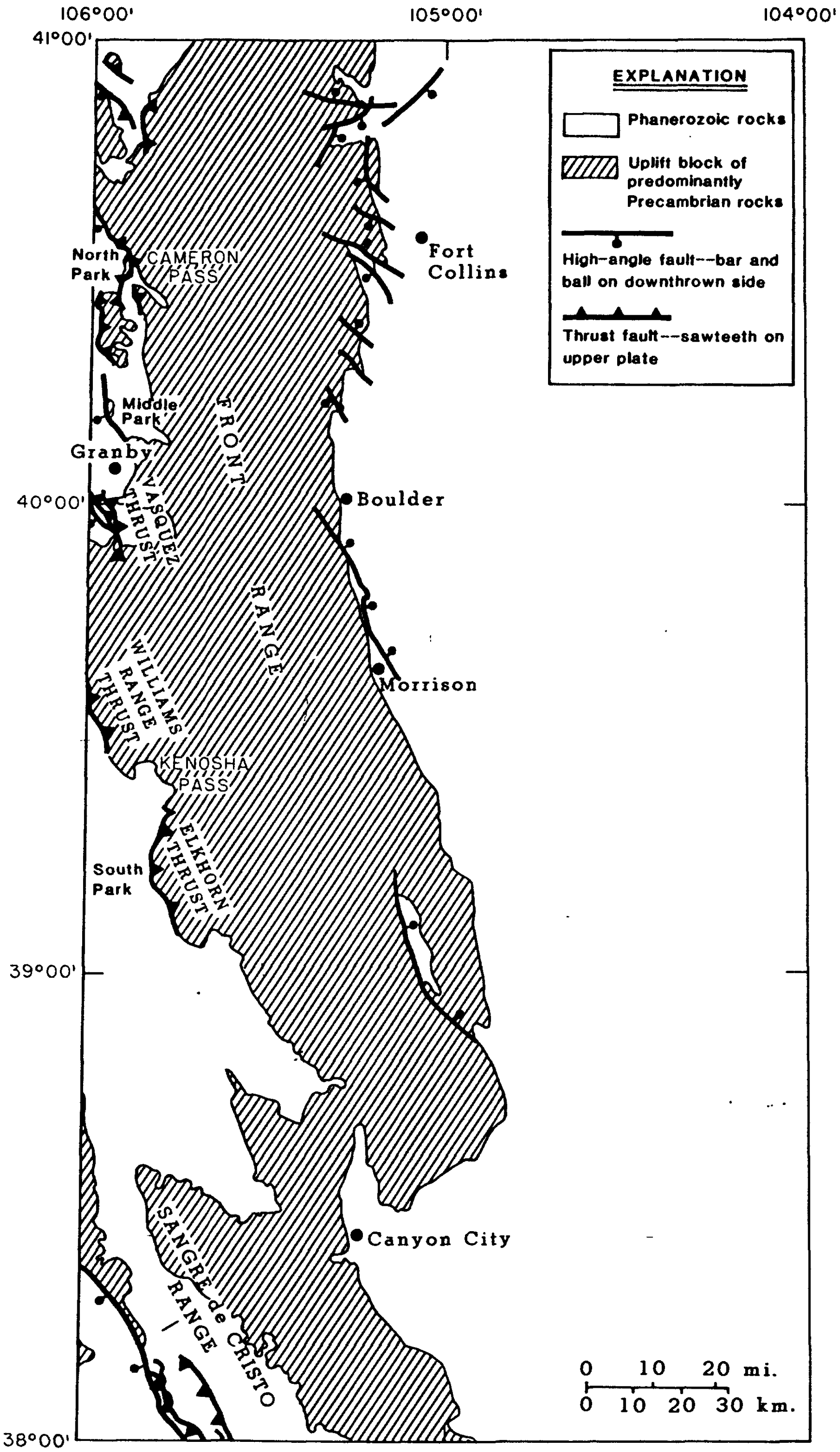

Figure 14.--Generalized geologic map of the Front Range, Colorado, showing Laramide uplift structures (simplified from Tweto, 1976).

Precambrian rocks above and over a thick section of shaly Jurassic and Cretaceous rocks. Exposures in the Roberts Tunnel permitted detailed observation of structural features in and adjacent to the fault zone (Wahlstrom and Hornback, 1962). The sedimentary rocks are described as sheared and plastic, as expected of ductile materials, but granitic rocks in the upthrust block are shattered. Over a distance of 3,400 m east of the thrust there are numerous faults in Precambrian rocks with an average spacing of 3.3 m. The thrust plane dips 30^{o} east at this level. The type of deformation is probably similar to the north along the thrust. Ductile rocks in the footwall do not appear to have structural permeability, but the highly fractured Precambrian rocks of the hanging wall appear to have favorable permeability. Miocene rocks of the Troublesome and North Park Formations cover the thrust zone and record renewed fault movement (Izett, 1975; Howard, 1966). The Miocene rocks are tuffaceous, part of a once-extensive Tertiary volcanic field in the area (Izett, 1975), and would possibly have been a good source for uranium. Cretaceous rocks in North Park contain oil fields, and thus might have been a source of hydrocarbons as a potential agent for uranium reduction. In conclusion, structurally high portions of the Williams Range thrust in the upper plate appear to be a favorable structural target for Copper Mountain type deposits.

Elkhorn thrust.--The Elkhorn thrust at the eastern margin of South Park has a known length of more than 60 km but the fault itself is very poorly exposed (Stark and others, 1949). It places Precambrian rocks above and to the west of chiefly Cretaceous rocks, but also deforms the Upper Cretaceous and Paleocene Denver Formation, which formed in a basin created by earlier Laramide uplift of the Front Range to the east (Sawatsky, 1964). The interpreted fault dip is less than 25^{o} east to the east in the southern area and 45^{o}-60^{o} east at the north end where it is interpreted to merge with the Williams Range thrust (Wyant and Barker, 1976). Broad open folds related to the thrust occur in the footwall block and to the west of the fault. Other reverse or thrust faults occur within 15 km to the west of the Elkhorn thrust (Ettinger, 1964; Wyant and Barker, 1976), and some produced overturned synclines below thrust planes, according to Ettinger's (1964) interpretation of oil well data.

According to the working hypothesis, the upthrust block of Precambrian rocks appears favorable for several reasons. The Elkhorn structure and brittle rock properties appear favorable for the development of Copper Mountain-type deposits. Middle Tertiary tuffaceous rocks of the Thirtynine Mile Volcanic field (Epis and others, 1976) probably covered much of the Elkhorn thrust; these rocks also occur in Tertiary paleovalleys that contain uranium deposits, such as in Tallahassee Creek district about 50 km to the south (Epis and others, 1976), and are a likely source of uranium. A uranium deposit occurs in fractured Precambrian rocks above the Elkhorn fault at Muley Gulch, 11 km northeast of Hartsel. Also, numerous radioactive localities and uranium deposits occur in fractured Precambrian rocks at Kenosha Pass, (fig. 14) where the Elkhorn thrust appears to terminate in high angle fractures that seem to rejuvenate a Precambrian joint direction (Trimble, 1964). Also, two high angle reverse faults are mapped by Barker and Wyant (1976) 3 km west of Kenosha Pass; several small uranium deposits occur in fractured Proterozoic Y Silver Plume Granite of the Kenosha batholith 0 to 2 km northeast of the mapped reverse faults, in positions similar to the Copper Mountain deposits (fig. 15). The footwall of the Elkhorn thrust zone does not appear favorable because approximately 3 km of clay-rich sediments occur above the uppermost possibly brittle sandstone (Upper Cretaceous Dakota Formation) and a total of 6 km of predominantly ductile shales overlies brittle Paleozoic rocks.

<u>Northeastern flank of Front Range</u>.--The eastern range front from approximately Morrison, Colorado, north to the Wyoming border has been described and interpreted by many authors (see Boos and Boos, 1957; Berg, 1962; Prucha and others, 1965; Matthews, 1976; Van Horn, 1976; Matthews and Work, 1978). The southern part, from Morrison north to Boulder, appears to be a high angle reverse fault dipping 50° or more to the west, and some folding and overturning may exist below the fault (Berg, 1962; Van Horn, 1976). North of Boulder the range-front structure evolves into a series of faults and folds with northwest trend. Early observers proposed thrust faulting and compression, but recent interpretation (Prucha and others, 1965; Matthews, 1976; Matthews and Work, 1978) demonstrate the predominance of uplift and drape folding. Basement blocks underwent brittle faulting, not folding, and rotation.

The northeastern Front Range uplift does not appear favorable for large amounts of structural permeability due to brittle deformation in either upfaulted or downfaulted blocks for some of the following reasons. The most likely angle of reverse faulting is very steep, probably too steep to produce

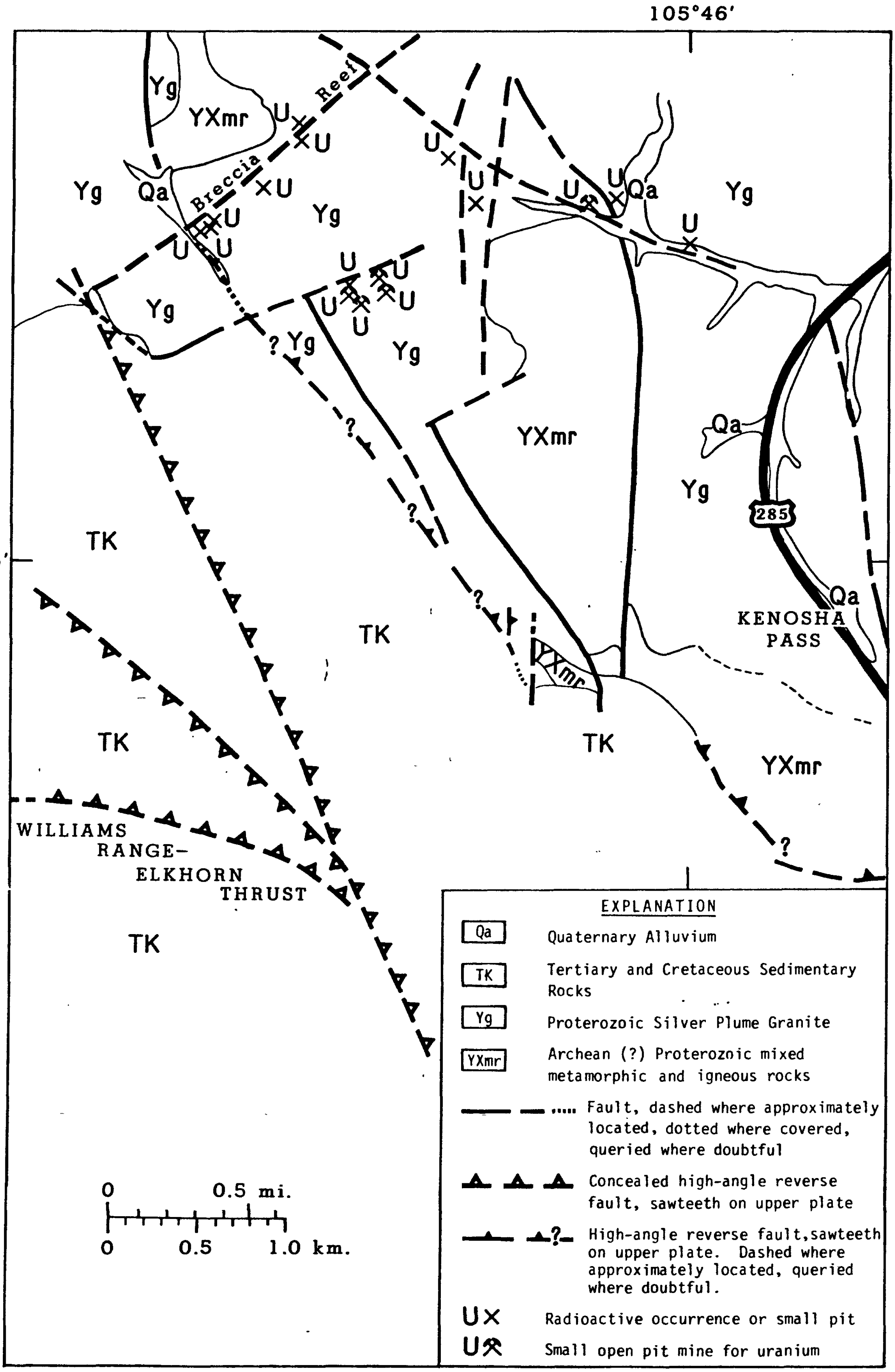

Figure 15.--Geologic map and uranium occurrences in the Kenosha Pass Area. Geology from Barker and Wyant, 1976, with additions by J. T. Nash and M. R. Handy, 1979.

abundant fracturing in the uplifted block, as reviewed earlier in the section on experimental studies. The downfaulted block contains about 4 km of clay-rich sedimentary rocks that are ductile, and also very little structural permeability would be expected. Most of the geology fits Stearns' (1978) category of unattached, ductile section (reviewed earlier) which is the least favorable for development of structural permeability. This discussion does not consider the complex reactivated faults in Precambrian rocks which are favored sites for Schwartzwalder mine-type uranium; that is another structural and genetic environment.

Middle Park--Never Summer Range.--Several thrust faults occur in the southeastern corner of the Greeley and northwestern Denver $1^{o}x2^{o}$ quadrangles in which Precambrian rocks are thrust over Jurassic to Middle Tertiary sedimentary rocks (Tweto, 1957; Ward, 1957; Izett, 1975; O'Neil, 1975). The Vasquez thrust carried Precambrian rocks over Jurassic Morrison to Cretaceous Niobrara Formations on an undulating thrust surface that generally dips only 5^{o}-10^{o} east. Where the thrust is entirely in Precambrian rocks the fault dips about 45^{o} east (Tweto, 1957). In places the Vasquez thrust breaks up into as many as four strands. The Stillwater fault is termed a thrust by Izett (1975) because in places it has flat dip, but in other places, especially near the basement, it has steep dip (Izett, 1974). Laramide faults in the area were reactivated in Middle Tertiary, often with different sense of movement (G. A. Izett, oral commun., 1979). The Never Summer thrust, and several others probably related to it in the Cameron Pass area, are low angle thrusts which moved Precambrian rocks over Cretaceous and Paleocene rocks (Ward, 1957). The thrusts are deflected up as they cut anticlines and sag down through synclines, as Tweto (1957) observed for the Vasquez thrust. The Never Summer thrust is deformed by high angle faults related to intrusion of the Tertiary Mt. Richthofen stock (R. C. Pearson, oral commun., 1979). The upper plate of the Never Summer thrust which is not strongly folded, moved westward during Laramide time (O'Neill, 1975). Tweto (1957) summarizes the tectonic stresses as predominantly horizontal and shallow producing overthrusts that transported a thin upper plate in a westerly direction. From these descriptions it appears that these thrusts were related to basement uplift, but are very high in the structures where thrust planes are subparallel to bedding. This environment is not favorable for development of tectonic permeability, particularly in ductile rocks.

Sangre de Cristo Range.--Structural details of this spectacular uplift are inadequately known, but available descriptions mention thrusts and high-angle faults (Litsey, 1958; Taylor, 1975; Scott and others, 1978). The limestone, dolomite, and quartzite Paleozoic section is about 300 m thick, is essentially like that in the Marshall Pass district described earlier, and the predominantly brittle lithologies should be investigated for possible brecciated zones. Mid-Tertiary volcanic rocks covered the range prior to uplift, which occurred less than 29 m.y. ago (Taylor, 1975). Most of the general structural and lithologic features of the Pitch mine environment may be present, hence the Paleozoic section looks favorable. However, the extreme relief would probably create hydrologic conditions that would tend to destroy uranium deposits, although downward migration and even enrichment of uranium in the late Tertiary is a possibility.

Summary

Fractured and brecciated rocks created during upthrust faulting are a favorable setting for uranium deposits as at Copper Mountain, Wyoming, and the Pitch mine, Colorado. Brittle deformation at shallow depth (<6 km) in reverse or thrust faults often is in broad zones with geometries amenable to mass mining, rather than in narrow zones characteristic of normal faults. According to observations of mineralized and unmineralized structures, experimental deformation, and structural analyses, two structural locations are most favorable for development of widespread structural permeability: (1) the frontal lobe zone above arching upthrust faults, as at Copper Mountain; and (2) below the upthrust fault where sedimentary rocks are folded or overturned, particularly if the section is attached to the basement as at the Pitch mine. In both cases brittle lithologies such as dolomite, quartzite, granite, gneiss, or crystalline and lithified volcanic rocks are required for faulting and brecciation rather than folding or thinning.

The geochemical environment of these shallow fracture zones is supergene, but either reduced or oxidized uranium minerals could have precipitated. Possible reductants might have been sulfide (Nash, 1979), hydrocarbons (Yellich and others, 1978), or possibly organic carbon. Post-uplift volcanic rocks, which appear to have been produced by the same plate tectonic processes that caused the uplift, covered the fracture zones and were viable sources of uranium, as is often proposed for sandstone deposits in adjacent basins.

Fracture zones that are possibly favorable for containing uranium deposits can be selected from geologic maps at scales from 1:500,000 to 1:24,000, and supplemented by detailed studies. Features such as reverse or thrust faults, uplifted blocks, and brittle lithologies should be interpretable from maps. More specific, but critical, aspects such as curvature of the fault plane and folding of rocks in the lower plate are generally difficult to define precisely from field observations, but should be investigated. The descriptions and interpretations reviewed in this paper should provide guides for selecting and interpreting exploration targets. Obviously the structural hypothesis described in this paper can be refined and made more specific by including additional factors, such as geochemistry and rock alteration.

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