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Mineral resource assessment of undiscovered mineral deposits for selected mineral deposit types in the Kaibab National Forest, Arizona

by

James D. Bliss[1]

with a section on

Mineral resource assessment of solution-collapse breccia pipe uranium deposits

by

James D. Bliss[1] and Charles T. Pierson[2]

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[1] U.S. Geological Survey, Tucson, Arizona
[2] U.S.Geological Survey, Denver, Colorado

EXECUTIVE SUMMARY

Metallic and nonmetallic resources of the Kaibab National Forest, Arizona
Assessment by the U.S. Geological Survey, 1993

GENERAL

- The Kaibab National Forest (KNF), located on the Colorado Plateau, is an area largely devoid of base- and precious-metal mineral deposits.
- Previous assessment of the Grand Canyon region for uranium deposits suggests that the KNF is in an area with undiscovered uranium resources comparable to the San Juan Basin, historically the most productive uranium area in the United States.
- Quantitative probabilistic mineral resource assessment in the KNF is only possible for uranium due to the absence of appropriate models or to the poor-quality of models for other mineral deposit types (e.g., strata-bound copper, manganese deposit types, replacement iron, bedded gypsum, limestone, flagstone, ashlar, basalt, cinder, scoria, and pumice).
- Industrial minerals, and flagstone production in particular, have been produced in the KNF for about 100 years.
- Industrial minerals are the likely focus of future production.

URANIUM

- Quantitative assessment of uranium in undiscovered solution-collapse breccia pipe deposits is made using the deposit-size-frequency method (DSF, option C), a modification of a technique developed for NURE (National Uranium Resource Evaluation).
- The mean unconditional endowment of 211,000 metric tons (233,000 shorts tons) U_3O_8 for undiscovered solution-collapse breccia pipe uranium deposits in the KNF is 20 percent of the total mean uranium endowment previously predicted for the Colorado Plateau.
- The endowment for the KNF is a portion of the total endowment previously predicted for the Grand Canyon Region; <u>not</u> an additional endowment.
- ***The North Kaibab Ranger District (fig. 1) contains approximately half of the*** undiscovered uranium endowment in the KNF.

INDUSTRIAL MINERALS

- Significant past production of flagstone occurred in the Williams District (fig. 12); future production likely will be from extensions of known deposits.
- Outcrops in permissive tracts (fig. 12-13) for flagstone with surface slopes greater than 35 degrees are highly unlikely to be used as future quarry sites.
- Two small areas of high calcium limestones suitable for cement are recognized (fig. 3) in the North Kaibab Ranger District.
- Bedded gypsum deposits are permissive in two different formations in the North Kaibab District (fig. 7) and the Tusayan District (fig. 8); undiscovered deposits probably are likely not compatible with the grade and tonnage model.
- Substantial amounts of cinder, scoria, pumice, and basaltic and related rock types used in construction are identified in the Williams and Chalendar Ranger Districts (figs. 6, 9,10). Suitability of basaltic and related rock types as dimension stone needs to be examined.

Non-technical Summary

The assessment is based on geologic knowledge and data as of 1993--it suggests that little future exploitation in the Kaibab National Forest (KNF)(fig. 1) can be expected for base- and precious-metal deposits (p. 2-5,8). However, the KNF is located in a region with significant undiscovered uranium resources and, given appropriate market conditions, exploitation could occur particularly in the North Kaibab Ranger district (p. 30-33). Deposit types for other metals (manganese, iron) are either small or rare and are unlikely to have much of a role in the economy of the KNF (p. 6-7).

Industrial minerals have a long history of production in the KNF. Production of sandstone used as ashlar (building stone), but mostly for flagging, has occurred for at least 100 years and sales have been world-wide. Production of flagging could continue into the future, likely from extensions of known workings. Demand for flagging in the construction industry is dependent on fashion, and therefore is not easily predicted. Due to low unit value, production occurs only in surface quarries and on hillsides with slopes less than 35 degrees. Outcrops forming cliffs are not workable. The volume of possible extensions of known deposits is not known. Methods to assess undiscovered flagging deposits are not available nor could they be developed using available data (p. 25-26).

Cinder, scoria, pumice, and basalt are extensive in the KNF, particularly in the Williams and Chalendar Ranger Districts (fig. 6, 9, 10). Cinders are used as road metal due to the lack of significant sand and gravel in the KNF. Younger cinder cones have the best quality material and are easily recognized. Cone geometry can be used to predict whether cinders can be easily mined (p. 17). Future production from cinder, scoria, pumice, and basalt is likely to occur in the readily accessible widely recognized deposits at the surface. No assessment of undiscovered deposits of these types were made.

Geology permissible for the occurrence of gypsum deposits is present in the KNF (fig. 7, 8) and known deposits are found adjacent to the KNF. If undiscovered deposits are present, their size would likely be overestimated by present models.

High-calcium limestone, likely appropriate for cement manufacture, occurs in the North Kaibab Ranger District (fig. 3), but additional analysis specific to the two areas of outcrops would be needed.

Sources of construction materials are widely available from several formations in the KNF. Methods to assess undiscovered deposits of construction and dimension materials are not available.

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INTRODUCTION

The Kaibab National Forest (KNF), Arizona, contains approximately 1.6 million acres (650,000 hectares (ha)) in four Ranger Districts (fig. 1). The purpose of this assessment is to provide information useful to the Forest Service land managers concerning the quantity of metals and materials in deposits yet to be discovered in the KNF. Of course, known deposit types in or adjacent to the KNF are useful in identifying appropriate deposit types. Two different approaches are used: one for metals and industrial minerals and a second for uranium.

Quantitative mineral resource assessments require appropriate mineral deposit models like those successfully used for assessing metal and industrial mineral deposit types (Cox and Singer, 1986; Bliss, 1992). The procedure for assessing mineral resources as described by Singer and Cox, (1988) and Singer and Ovenshine (1979) allow prediction of the quantity of materials in undiscovered deposits at different levels of certainty (Root and others, 1992; Spanski, 1992). The U.S. Bureau of Mines also has successfully used assessment results in their analysis of economic potential of future mineral development within an area (e.g., the East Mojave National Scenic Area, California (U.S. Bureau of Mines, 1992) and Kootenai National Forest, Idaho and Montana (Gunther, 1992)). For this strategy to work, grade and tonnage models are first necessary; secondly an **estimate of numbers of undiscovered deposit must be made. Deposit types** lacking grade and tonnage models can not be assessed.

The assessment of uranium in solution-collapse breccia pipe uranium deposits is handled differently. The method used and the assessment results are both given in a separate section by Bliss and Pierson. The predicted undiscovered uranium from this deposit type does not represent uranium endowments additional to those reported by Finch and others (1990) but they suggest what portion of their endowment is found within the KNF.

Industrial minerals have been and are likely to be the primary mineral commodity type produced in the future in the KNF. Modeling industrial mineral deposit types has just begun (Orris and Bliss, 1991; Orris and Bliss, 1992) and it does require development of different types of mineral deposit models (Orris and Bliss, 1989). In order to assess these materials, mineral deposit models need to be developed. Unfortunately, mineral deposit models are not available for most of the industrial mineral commodity types found in the KNF. Since flagstone is an important commodity, with a long production history in the KNF, an attempt was made to develop models for it, but was unsuccessful due to the very poor quality of readily available data.

Data about mineral deposits found in or adjacent to the KNF have come from various sources. A general source for mineral deposit data is the Mineral Resource Data System (MRDS), a world-wide computer database with locality and commodity data which is available to the public and other government agencies via the U.S. Geological Survey Minerals Information Offices located in Tucson, Arizona; Reno, Nevada; Spokane, Washington; and Washington, D.C. Additional sources for industrial minerals include Phillips (1987) and Houser (1992).

The text of the report will first address the metallic mineral deposit types permissive in the KNF. This will be followed by a discussion of industrial minerals. An assessment of uranium in undiscovered solution-collapse breccia pipe uranium deposits is in the last section.

Because the assessment will be released as an Open-File Report before it is released as a Bulletin, manuscripts prepared by other contributors to the Bulletin are cited as written communications.

STRATA-BOUND COPPER

Geology

A detailed summary of the strata-bound copper deposits in the Kaibab Formation (Van Gosen and Wenrich, written commun., 1992) is the source of the following summary unless otherwise noted. The deposits consist of malachite, azurite, chalcopyrite, and chalcocite coatings on bedding planes and fracture surfaces, and disseminated as the matrix of the chert breccia in the upper part of the Harrisburg Member (Bissell, 1972) of the Kaibab Formation, which is commonly present as a chert-rubble erosion surface in much of the Grand Canyon region. Hopkins (1990) recognizes gypsum, dolostone, sandstone, redbeds, and chert with minor limestone in the upper part of the Harrisburg Member. Other metallic minerals include bornite, cuprite, pyrite, hematite, limonite, and manganese oxides. Sutphin (written commun. to Van Gosen and Wenrich) suggest that tenorite, covellite and uraninite may also be present.

Individual prospects are commonly circular; all are in flat-lying chert breccia or limestone breccia. Scott (1992) provides more detailed summaries of some individual prospects and workings. Mineralized zones are thin---usually between 0.25 to 1.0 m (Gibbons,1952 as cited in Van Gosen and Wenrich, written commun., 1992). Billingsley (written commun. to Van Gosen and Wenrich) noted that mineralization is found at about the middle part of the Harrisburg Member in the Francis mining district (fig. 2); however mineralization is scattered throughout the unit in the Warms Springs mining district (fig. 2). Billingsley suggested that dissolution of gypsum may have created channels for mineralizing solutions. Cherty limestone and breccia host rocks of copper mineralization are also thicker adjacent to some faults than elsewhere in the Harrisburg Member but this suggestion needs additional study (Wenrich and others, 1986).

Definition of permissive areas

Identified strata-bound copper deposits have a north-south alignment best represented by the properties of the Francis mining district (fig. 2). No obvious controlling structures have been identified (Scott, 1992). Other strata-bound copper deposits are recognized in the Pine Springs mining District to the west of the KNF in the Hualapai Indian Reservation (Van Gosen and Wenrich, written commun., 1992).

Gypsum, a possible source of sulfur for the mineralized zones, is an important part of the Harrisburg Member to the west of the KNF; to the east of the KNF, the gypsum thins and becomes silty. East of a north-south line extending from a point about 5 miles west of Page, Ariz. to a point about 12 miles west of Flagstaff, Ariz. (Sorauf and Billingsley, 1991, fig. 5) the Harrisburg Member interfingers with the underlying Fossil Mountain Member (Bissell, 1972). The Harrisburg Member was deposited during a "cyclic westward retreat of the Kaibab sea" (Hopkins, 1990, p. 244). Billingsley (written commun. to Van Gosen and Wenrich) noted that the various internal units of the Harrisburg Member intertongue and become one unit east of a north-south line from Jacobs Lake to Grand Canyon Village. The facies change is just west of Warm Spring Mining District and just east of the the Francis Mining District (Van Gosen and Wenrich, written commun., 1992; fig. 2). This boundary is similar to the change from a carbonate shelf depositional environment to restricted mixed shelf in the underlying Fossil Mountain Member (Hopkins, 1990, fig. 7).

A generalized interpretation of these various facies changes has been used to mark the eastern boundary of the permissive area for strata-bound copper deposits (fig. 2). The extension of the boundary into the Willams-Chalendar Ranger District utilized the overall trend of the facies change from the north, with some modification in consideration of the suggested paleogeography of the Fossil Mountain Member.

Known strata-bound copper deposits

The two principal mining districts for strata-bound copper in, or adjacent to, the KNF are the Warm Springs (Jacob Lake) mining district in the North Kaibab Ranger District, and the Francis (Canyon) mining district in the Tusayan Ranger District (fig. 2). The Warm Springs Mining District includes at least ten described properties (Black Beauty, Kaibab Group, Kennedy, Little Buck, Mackin Group, Petroskey Claim Group, South Phantom Nos. 1-6, Spotted Bull, Apex Copper, and Copper Queen) scattered over an area of approximately 1,700 ha. The Francis Mining District includes at least seven described properties including the Anita Mine (Emerald Mine), Blue Bonnet Mine, Copper No. 1 Mine, Grand Canyon property, Packrat Claim, Rowes Well Property, and Tellstar Claims. For modeling purposes, the Warm Springs, and the Francis Mining Districts are treated as mineral deposits (fig. 2).

Models for strata-bound copper deposits

Estimates for the Warm Springs Mining District based on the compilation by Van Gosen and Wenrich (written commun., 1992) suggest that 29,000 mt of ore containing 6.6 percent copper, 19 g/mt silver and 0.24 g/mt gold was produced. Based on data in Welty and others (1989), production is estimated to be on the order of 33,000 mt of ore containing 6.4

percent copper, less than 0.01 percent lead, 18 g/mt silver, and 0.22 g/mt gold.

Estimates for the Francis mining district based on the compilation by Van Gosen and Wenrich (written commun., 1992) suggest that 3,000 mt of ore at 13 percent copper, 16 g/mt silver, and 0.14 g/mt gold was produced. Based on data in Welty and others (1989), production is estimated to be on the order of 11,000 mt of ore at 3.0 percent copper, 0.021 percent lead, 11 g/mt Ag and 0.28 g/mt gold. Some production from remnant solution-collapse breccia pipe uranium deposits in the same area may contribute to the larger production figures. Reserve data are not available in either case.

In a general way, the geologic descriptions of the deposits indicate that they can be classified as sediment-hosted Cu (Cox, 1986); however, both the Warm Springs and Francis mining districts are too small--in fact they are both smaller in size than the smallest deposit in the grade and tonnage model (Mosier and others, 1986, fig. 154). Both copper grades (somewhat distorted due to up-grading by hand-sorting) and silver grades are consistent with the grade and tonnage model. However, both the Warm Springs and Francis mining districts have byproduct lead, and gold production which is missing in the model of Mosier and others (1986).

Estimate of numbers of undiscovered strata-bound copper deposits

Lacking an appropriate grade and tonnage model for these deposits, an estimate of the numbers of undiscovered deposits is not made. Mineralization at Jacobs Lake (Warm Springs) is found in an area of 1,700 hectares (6.6 square miles). Mineralized areas of this size in the Harrisburg Member exposed at the surface probably would have been found by prospectors. Undiscovered deposit are unlikely to be present in the North Kaibab Ranger District or the Tusayan Ranger District. On the other hand, the Harrisburg Member is covered by the San Francisco volcanic rocks in the Williams and Chalendar Ranger District. The size of the permissive area in this latter ranger district is somewhat unclear because the facies change boundary in this area is not well defined but would be restricted to the area of SED-3.

MISCELLANEOUS METALLIC DEPOSIT TYPES

Strata-bound manganese and related deposit types

Two manganese deposits have been described in formations found in the KNF. The deposits are found well outside the KNF proper. The Johnson and Hayden deposit (35° 40' 48" N, 109° 57' 36" W), northwest of the Williams and Chalendar Ranger Districts, was classified by Welty and others (1989) as a strata-bound and (or) stratiform deposit with minor manganese production in 1952-1953. Farnham and Stewart (1958) classified the deposit as a breccia. Dorn (1969) estimated that more than 300 long tons (lt or mt[1]) were produced at a manganese grade of 28 percent, and that less than 1,000 lt (mt) remain at the site with a grade less than 15 percent manganese. The deposit is hosted by the combined Kaibab and Toroweap Formations as shown by Moore and others (1960).

The Long Valley deposit (34° 34' 12" N, 111° 19' 48" W), southeast of the Williams and Chalendar Ranger Districts, was classified by Welty and others (1989) as strata-bound and (or) stratiform with production prior to 1954. Farnham and Stewart (1958) classified the deposit as a replacement and residual deposit. Dorn (1969) estimated that more than 3,300 long tons (3,400 mt) were produced at a manganese grade of 32 to 42 percent and that less than 2,000 lt (mt) remain at the site with a grade around 10 percent manganese. The Kaibab Formation at Long Valley has manganese in thin beds and nodular masses, some which are as large as 100 tons (Dorn, 1969). Farnham and others (1961) described manganese in soil and gravel which may be detrital. Dorn (1969) also suggested that some manganese may be precipitated as manganese oxides from groundwater.

Grade and tonnage models for these manganese deposit types are not available. The permissive tracts (LSK-1 to LSK-8) for these manganese deposit types are the same as for limestone in the Kaibab Formation (figs. 3-5).

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[1]One long ton is equal to 1.016 metric ton; thus there are no differences between long tons and metric tons at two significant fi ures.

Replacement iron deposit

Iron has been mined in the Redwall Limestone, approximately 20 km west of the Williams and Chalendar Ranger Districts (Klemic, 1933). The Seligmann iron district (35° 06' 00" N, 112° 52' 48" W) was classified by Welty and others (1989) as stratiform. Harrer (1964) described the deposit as a replacement along the contact between the limestone and an andesite porphyry sill. The deposits was worked for hematite (with grades between 55 and 68 percent Fe) for use as mineral pigment. This is the only known deposit of this type hosted by the Redwall Limestone in Arizona.

A grade and tonnage model for replacement iron deposits is not available. Tracts LSR-1 and LSR-2 delineated for limestone use the Redwall Limestone to define permissibility (fig. 3). The presence of an intrusive like that at Seligmann would be necessary but may not be seen in outcrop. If other limestone-bearing formations are also permissive, tracts LSK1-LSK8 (figs. 3-5) are possibly permissive for replacement iron deposits as well. Intrusives become much less common at the geographic position of tracts LSR1 and LSR2 in the Colorado Plateau. However, tracts LKS-3 to LSK-8 are adjacent to the San Francisco volcanic field, and the likelihood of intrusives (including sills) is much higher. Undiscovered deposits of this type are more likely in this area assuming the Kaibab Formation is an appropriate host.

Iron veins associated with rhyolite

Workings, including a shaft at least 15 feet (4.6 m) deep, and pits occur at Slate Mountain (fig. 6) located approximately 2 km northeast of the of the Williams-Chalendar districts (Lockrem, 1983). The workings are located in a contact metamorphic zone in which rhyolite intrudes into the Martin Formation. The zone is characterized by bleaching, brecciation, and magnetite and hematite mineralization occurring in concordant and discordant veins (Lockrem, 1983). Trace amounts of copper (300-3000 ppm), lead (1000-3000 ppm), and zinc (60-1200 ppm) were detected in four particularly well-mineralized samples (Lochrem, 1983).

No descriptive or grade and tonnage models have been developed for iron veins associated with rhyolite. The RD tracts (fig. 6) are permissive for the deposits type given that the Kaibab Formation would react similarly to the Martin Formation. If any deposits exist they are unlikely to be exposed because the tracts are mostly covered by volcanic rocks.

Remnant solution-collapse breccia pipe uranium deposits

Solution-collapse breccia pipe uranium deposits are usually considered as a source of uranium (see last section). However, when these deposit become exposed at the surface, they are depleted in uranium and enriched in copper by supergene processes (Finch and others, 1992).

The number of remnant solution-collapse breccia pipe uranium deposits with data (n=12) is too few to allow development of a stable grade and tonnage model. However, the available data--all from deposits in the Colorado Plateau--allow the following overview of deposit sizes and grades.

It will come as no surprise that these remnant deposits (e.g., Orphan Lode, Grandview, Copper Mountain) are, on average, two orders of magnitude smaller (median size of about 1,000 mt) than uneroded solution-collapse breccia pipe uranium deposits which have a median size of 230,000 mt (Finch and others, 1992, fig. 21). The largest remnant deposit is 11,000 mt. These remnant deposits are worked for copper; grades are usually between 3.2 and 33 percent. The median grade is 10 percent copper. Other base metals produced as by-products include lead in about half the deposits and zinc in about a third. Lead grades are less than 0.6 percent and zinc **grades are less than 0.8 percent. *Silver is produced in nearly all the*** deposits with grades between 9 and 270 g/mt; the median grade is 50 g/mt. Gold is produced in about a third; the grades are quite low--usually less than 250 ppb. Remnant solution-collapse breccia pipe uranium deposits do not appear to produce uranium.

Remnant solution-collapse breccia pipe uranium deposits are, by definition, a deposit type found at the surface. All surface exposures of the Kaibab Formation (tracts LSK-1 to LSK-8; figs. 3-5) are permissive for these deposits. Although they are small, these deposits will be difficult to miss. Forested areas or those covered by volcanic rocks, however, may contain a number of undiscovered deposits of this type.

LIMESTONE

Background

Most limestone is produced for making cement, processed for lime, or crushed for use as aggregate in construction. Limestone or other calcareous rocks make up 75-80 percent of the raw material used to make cement (Harben and Bates, 1984). Limestone is composed of 50 percent or more calcite plus dolomite, with calcite greater than dolomite. Ultra-pure limestone contains greater than 97 percent $CaCO_3$; high calcium limestone contains greater than 95 percent $CaCO_3$ (Harben and Bates, 1984). Cement preparation requires not only $CaCO_3$, but also silica, alumina, and iron, which may be contributed by the clay, sand, and chert commonly found in limestones. These components (as well as other materials) need to be added during cement manufacture if they are absent or are insufficient in the limestone. Dolomite is tolerated in limestones up to about 5 percent of the raw material if used for cement (Harben and Bates, 1984).

Other uses of limestone or derivative products (e.g., lime) include dimension stone, riprap, road metal, roofing granules, fillers (paper, asphalt), filters (water treatment), absorbents (gold leaching), ceramics, flux (steel), agriculture, glass, and well drilling fluids (Keith, 1969c; Lefond, 1983). In the Arizona, the copper industry uses lime in flue gas desulphurisation (O'Driscoll, 1990).

Geology

In Arizona, the Escabrosa and Redwall Limestones of Mississippian age are the best for chemical and industrial use (Keith, 1969c). The limestones are both massive, strong, high calcium, and low dolomite rocks with chert nodules and bands as the chief impurity. These two limestones have been the principal source of material for cement production in Arizona (Keith, 1969c).

Material from the Kaibab Formation has been used mainly as aggregate and building stone (Keith, 1969c), but it may have other uses. Material from the Kaibab Formation quarried near the top of the formation in the vicinity of Walnut Canyon National Monument (west of the Williams and Chalendar Districts) in 1952-53 was used as interior and exterior veneer (Kiersch, 1955). Chert and siliceous layers are found locally in some abundance in the material and may depreciated its use as veneer.

The stratigraphy and geology of the Kaibab Formation have been well studied because of its extensive surface exposure as cap rock in the Grand Canyon area, including both the North Kaibab and Tusayan Ranger Districts (fig. 1). However, a detailed review of this large body of work has not been made to determine how useful existing chemical analyses, and other factors are for choosing limestone quarries sites. The Kaibab Formation is a complex shallow-marine unit (Hopkins, 1990) that contains a number of lithologic facies--calcareous to siliceous--and is 90-120 m thick along the rim of the Grand Canyon. With both diagenetic silicification and dolomitization, the Kaibab Formation contains a complex mix of material in terms of end use. Facies changes introduce additional complexity. The Kaibab Formation to the west of the KNF contains mostly limestone deposited in an open-marine environment; to the east of the KNF, the Kaibab Formation contains dolomitic mudstone, sandy dolomite, and sandstone representative of a restricted mixed shelf environment (Hopkins, 1990; Blakey and Knepp, 1988).

The Kaibab Formation is divided into two members--the lower Fossil Mountain Member and the upper Harrisburg member (Hopkins, 1990). In the vicinity of the Grand Canyon, the Fossil Mountain Member, 75-105 m thick, is a cliff-forming cherty limestone. The Fossil Mountain is not exposed at the surface in the Tusayan Ranger District, but is exposed below the rim in the Grand Canyon National Park. It likely occurs in the North Kaibab Ranger District and in the Williams-Chalendar Ranger Districts particularly along the south boundary of the KNF (Mogollon Rim). The Fossil Mountain member in the west part of the Grand Canyon area contains a normal marine fauna with sandstones making up less than 10 percent of the lithofacies, commonly near the base (Hopkins, 1990). In the west part of the North Kaibab and Tusayan Ranger Districts a sandy carbonate rock makes up 50 percent of the upper part of the Fossil Mountain Member, and the marine molluscan fauna is more typical of those found in restricted basins (Hopkins, 1990). Dolomite becomes more abundant. At the east edge of the Tusayan District the Fossil Mountain is approximately 75 percent sandstone or sandy dolostone (Hopkins, 1990).

The Harrisburg Member varies in thickness from 90 m in the western Grand Canyon area to 25 m east of the Tusayan Ranger District. It is exposed at the surface in the Tusayan Ranger district and is likely present at the surface in the North Kaibab Ranger District and in the Williams and Chalendar Ranger Districts. The upper surface of the Harrisburg Member is a chert-rubble erosion surface common to much of the Grand Canyon region. Limestone is minor; gypsum, dolostone, sandstone, redbeds, and chert are more abundant (Hopkins, 1990). It is not a promising source for limestone.

The crushing strength of limestone in the Kaibab Formation is reported in Kiersch (1955) to be between 4,500 and 9,400 pounds per square inch (PSI) (320 and 1,200 kilograms per square centimeter (kg/cm^2)) based on tests of 4 fine-grained, freshly quarried blocks. The average crushing strength is about 6,700 PSI (470 kg/cm^2). These samples were collected in the Navajo-Hopi Indian Reservations and may not be representative of limestone in the Kaibab Formation in the KNF.

Definition of permissive tracts

Several small patches of the Redwall Limestone crop out in the North Kaibab Ranger District and are delineated as LSR-1 and LSR-2 (fig. 3). The Kaibab Formation is widespread in the KNF and is found in the LSK series of tracts in all districts (figs. LSK1-NK8, fig. 3-5)

Improving the assessment for limestone

Limestone is one of a number of bedded industrial mineral deposit types that lack models or strategies for quantitative assessment. Therefore, an estimate of undiscovered limestone resources is not possible. All outcrops of the Redwall Formation in the KNF are permissive. A portion of the Kaibab Formation may be worked given information about limestone quality including impurities (i.e, chert concentrations, dolomite) and detail end-use specifications (cement, aggregate, and so forth).

BEDDED GYPSUM

Background

Gypsum, or hydrous calcium sulfate ($CaSO_4{\cdot}2H_20$), is the most abundant natural sulfate (Harben and Bates, 1984). Upon loss of water gypsum becomes anhydrite ($CaSO_4$). Use of anhydrite is minor when compared to gypsum although neither mineral is found without the other (Appleyard, 1983). Unfortunately, anhydrite represents the larger part of the world's extensive reserves of these sulfates (Appleyard, 1983). Calcined gypsum ($CaSO_4{\cdot}1/2H_20$) or plaster of Paris is an important product as a component of plasterboard. Uses of uncalcined gypsum are: as a retardant in cement; as a fertilizer; as a filler in paper, paint, and toothpaste; and in oil well drilling mud (Harben and Bates, 1984). Due to the wide availability of gypsum, only readily accessible deposits at the surface are being worked. Strip mining is the common extraction method, with some operations exceeding 50 m in depth (Raup, 1991). Proximity to infrastructure and markets is critical in deciding if a deposit will be worked, because transportation is a major contributive cost of the material for users. Gypsum and anhydrite constitute the largest known reserve of sulfur, although it is largely untapped and currently an uneconomic source of sulfur.

Geology

Gypsum and anhydrite occur as evaporites identified in rocks of Silurian through Quaternary age (Appleyard, 1983). The proportion consisting of anhydrite increases with geologic age of the enclosing rock. Thus, younger deposits are more likely to be worked because they contain more gypsum. Gypsum is commonly found associated with other evaporites. Due to its high solubility, primary gypsum deposits are subject to considerable post-depositional modification, recrystallization, and remobilization.

Known deposits and definition of permissive tracts

Two units found in the KNF contain evaporites, and that makes them permissive for gypsum deposits--Permian Kaibab Formation and the Triassic Moenkopi Formation. The Toroweap Formation is commonly included with the Kaibab Formation as was done herein.

The Harrisburg Member of the Kaibab Formation is exposed at the surface in the North Kaibab Ranger District, the Tusayan Ranger District, and the Williams and Chalendar Ranger Districts. Gypsum, along with dolostone, sandstone, redbeds, chert, and minor limestone compose the sequence (Hopkins, 1990). The member thickens to the west (up to 85 m) with significant bedded gypsum present. In fact, gypsum is mined from the Harrison member west of Las Vegas, Nevada at the Blue Diamond Hill Mine (Hopkins, 1990). A number of underdeveloped occurrence and at least one gypsum mine have been identified in either the Kaibab and (or) Toroweap Formations in northwest Arizona (Keith, 1969b). To the best of my knowledge, no significant amounts of gypsum have been identified in the Harrisburg Member in the KNF. However, the Kaibab and Toroweap Formations are permissive for bedded gypsum as outlined in LSK tracts (fig. 3-5) (see discussion under limestone for discussion of geology of the Kaibab Formation.)

Irregular gypsum lenses totalling 330,000 mt of material at a grade of 97.5 percent gypsum have been described by Keith (1969b) in the Moenkopi Formation (Keith, 1969b; table 31). This tonnage is much smaller than the size distribution of deposits used in the grade and tonnage model by Orris (1992); however, the gypsum grade in this deposit is within the grade distribution of the grade and tonnage model (Orris, 1992; fig. 36). No significant amounts of gypsum have been identified in the Moenkopi Formation in the KNF. However, the Moenkopi Formation is permissive for bedded gypsum as outlined in GM tracts (fig. 7-8).

Models for bedded gypsum

A descriptive model for bedded gypsum as an marine evaporite (Raup, 1991) is applicable to the type of deposit expected in the delineated tracts. This type of gypsum deposit is both the thickest and the most extensive in area. The deposits develop in marginal marine basin with periodic inflow of sea water (Raup, 1991). Deposits are associated with dolomite and halite.

The grade and tonnage model by Orris (1992) is based on data from 14 entities which include data from a mix of districts, areas, and single deposits. Ninety percent of the deposits have a size equal to or greater than 14 million mt; 50 percent have a size equal to or greater than 280 million mt; and 10 percent of the deposits have a size equal to or greater than 5.6 billion mt (Orris, 1992, fig. 35). Ninety percent of the deposits have a gypsum grade equal to or greater than 82 percent; 50 percent have a gypsum grade equal to or greater than 91 percent; and 10 percent of the deposits have a gypsum grade equal to or greater than 99.8 percent (Orris, 1992, fig. 36). While the grade distribution is likely applicable to undiscovered deposits, the size of deposits may not be so applicable for deposits of this type in the Moenkopi Formation given that the deposit described by Keith (1969b) is typical.

Estimate of numbers of undiscovered bedded gypsum deposits

No estimate of undiscovered deposits of this type was made. Deposits like those in the grade and tonnage model are large but it is unknown how extensive (or exhaustive) exploration has been for bedded gypsum deposits in the KNF. The presence of undiscovered deposits cannot be discounted.

SCORIA, CINDER, AND PUMICE

Background

Uses of scoria and cinder include those of aggregate, cinder block, concrete, landscaping, and railroad ballast. Two key properties make scoria and pumice valuable: light weight and insulating ability (Harben and Bates, 1984). Other uses include roofing granules, riprap, and road metal (Osburn, 1982). Pumice has somewhat more specialized uses than cinder. These include use as an abrasive material for dressing wood or metal and in domestic and industrial cleaning of surfaces (Keith, 1986d). Stone washed jeans are prepared using lump pumice to "abrade and soften denim" (Scott, 1992, p. 35).

Color of the cinder or scoria dictates how it is likely to be used in landscaping. Dark reddish brown material is found in the vent area; it becomes brown to dark gray with "iridescent surface coatings at intermediate distances" and becomes very dark gray to black in the outer edges of the cone (Osburn, 1982). These color changes are related to a decreasing ferric to total iron ratio varying from 95 percent in the vent area to 5 percent in the outer edges of the cone (Osburn, 1982).

Geology

Scoria, cinders, and pumice are all a product of explosive volcanism. All involve the rapid loss of dissolved fluids from viscous volcanic material on reaching the surface. The distinction between scoria and pumice is simply based on composition--mafic volcanic melts yield scoria while silicious melts yield pumice. When pumice is less than 0.16 inches (0.4 cm) in diameter, it is called pumicite and can be carried great distances in the atmosphere (Peterson and Mason, 1983). When scoria is less than 1 inch **(2.5 cm) in diameter it is called cinder (Harben and Bates, 1984).**

In general, scoria and cinder are deposited near the source volcanic vent. Less dense, finer grained pumice is carried farther away. The extremely fine-grained pumicite can travel hundreds of kilometers. Keith (1986d) noted that pumice is chemically comparable to rhyolite, quartz latite, and dacite. Deposits are commonly lenticular and are found interbedded with lava and tuff.

Definition of permissive areas

Cinder cones in the Williams and Chalendar Ranger Districts are part of the San Francisco volcanic field which extends to the east of Flagstaff (fig. 1). Wolfe, Ulric' and Newhall (1987) and Wolfe, Ulrich, Holm,and others (1987) prepared geologic maps of the northwest part and central part of the field. Newhall and others (1987) mapped the southwest part. These maps all show a portion of the KNF.

A large number of cinder and scoria pits are present in the Chalendar and Williams Ranger districts of the KNF. This material has been and will continue to be produced. Cinder and scoria associated with volcanic cones are a resource readily identified if present. In addition, the better quality material is usually found in, or adjacent to, the youngest cones, which makes this material easy to discover. In addition, the geometry of unworked cinder cones can be one key to understanding its potential for cinder and scoria (see Improving the assessment of discovered cinder cones). Wind-fall material may not be identified so readily.

Cinder cones are found in the northeast two thirds of the combined Williams and Chalendar Ranger Districts. Features described as cinder cones on the geologic map are shown in black (fig. 9). See the geologic maps by Wolfe, Ulrich, and Newhall (1987); Wolfe, Ulrich, Holm,and others (1987); and Newhall and others (1987) for detailed identification and location of cinder cones.

In the San Francisco volcanic field, pumice is likely to occur in major eruptive centers with andesite, rhyolite, and dacite volcanics. Such eruptive centers includes Sitgreaves Mountain, Bill Williams Mountain, and Kendrick Peak. Pumice deposits recognized on the east flank of Bill Williams Mountain are poor quality as compared to 14 sources of pumice in the United States and the world (Scott, 1992). The high density and low porosity of this pumice makes it suitable only for landscaping and in road construction (Scott, 1992). Delineation of areas permissive for pumice is based on areas with rocks of dacite and rhyolite composition (fig. 6).

Models for cinder, scoria, and pumice

Models for making quantitative predictions about undiscovered cinder, scoria and pumice resources have not been developed. While estimates of volume of material in identified cinder cones are possible, models characterizing the chemical and physical properties of the material are more difficult.

Improving the assessment of discovered cinder cones

Osburn (1982) showed that the ratio of height to basal diameter, or the aspect ratio, is usually between 0.1-0.2 for cinder cones which can be mined. Cones with lower aspect ratios contain more flows. Cones with an aspect ratio greater than 0.2 contain "agglutinate blocks" which makes extraction difficult (Osburn, 1982). Measuring aspect ratio from topographic maps can help identify which cinder cones should be considered initially as a source of cinder.

Scott (1992) found that roughly half of the 200 or more cinder cones in the Chalendar and Williams Ranger District have aspect ratios between 0.1 and 0.2. Scott (1992) also found that 75 percent of all pits are located on cones with aspect ratios between 0.1 and 0.2. No systematic relation was found by Scott (1992) between cinder cone composition type and the presences or absence of cinder quarries.

Estimate of undiscovered cinder, scoria, and pumice resources

Most of the cinder and scoria in the KNF is associated with identified cinder cones. Some finer-grained material may be located beyond the cones, but represents a small amount of material in comparison with matieral in identified cones. Some complex cones may be difficult to assess. A portion of each cone can also be expected to contain some vesicular flows and agglutinate fragments that will make extraction difficult (Harben and Bates, 1984).

No models have been developed for making quantitative assessments of cinder and scoria, so that evaluation of undiscovered resources is not possible. On the other hand, the KNF contains considerable number of cones with identified cinder and scoria resources which will be exploited before less accessible and presumeably smaller volume deposits are considered.

BASALT AND RELATED ROCKS

Background

The main historical use of basalt and other dark, fine-grained igneous rocks is as crushed stone in concrete and aggregate. "Basalt is...melted and cast into floor tiles and acid-resistant equipment for heavy industrial use" (Harben and Bates, 1984, p. 63). Basalt use as a dimension stone is dependent on fashion. In the past it was not used as dimension stone because it was thought to have a somber appearance (Keith, 1969a). However, dark colored stone has become fashionable and can demand a premium price. Quarrying basalt can be difficult due to its lack of joints and its tendency to blast into irregular sized and shaped blocks. Basalt and related rocks are the highest density material used as aggregate which precludes shipping it great distances.

Geology and definition of permissive tracts

Abundant Tertiary and Quaternary basalts, a criterion for identification of permissive areas, cover a large area of the Williams and Chalendar Ranger Districts (fig. 10), but are not present in the North Kaibab Ranger District. Several small basalt outcrops are found in the southern part of Tusayan Ranger District, of which at least two can be delineated at approximately 1:330,000-scale (fig. 11). All the remaining basalt and associated volcanic rocks are in the San Francisco volcanic field which was active during the Pliocene and Pleistocene (Newhall and others, 1987). Compositionally the material is basalt and basaltic andesite with lesser amounts of andesite, benmoreite, and dacite.

Assessment of basalt and related rock types

No models have been developed yet for making quantitative assessment of basalt and related rock types so an evaluation of undiscovered resources is not possible. On the other hand, the KNF contains considerable identified basalt and related rocks in accessible surface outcrops that will be exploited before less visible resources are considered. Possible suitability of basalt and related rock types as dimension stone in the KNF needs to be addressed and appropriate sampling made in future assessments.

FLAGSTONE AND ASHLAR

Background

Flagstone production in the KNF has been and will likely continue to be important. Models needed for making quantitative predictions about undiscovered flagstone and ashlar resources have not been developed previously. Several models for flagstone for this assessment were attempted but were found to be unsuitable. Needed data on the number and size of flagstone quarries are lacking. A crude model has been developed to characterize the size of quarried areas.

Flagstone production in Arizona

An estimate of total flagstone production in Arizona is complicated and only approximate due to: (1) incomplete reporting and the mixed nature of reporting made for dimension stone from sandstones, including with and without distinction between ashlar and flagstone; and (2) different reporting procedures for different time frames, some of which partly overlap in time.

Flagstone production in Arizona from 1952 to 1991 is estimated to be 210,000 mt based on data found in the U.S. Bureau of Mines Yearbook (1952-1968), Mineral Commodity Summaries (1989-1991), and Keith(1969e). Flagstone appears always to have been an important portion of the sandstone produced as dimension stone in Arizona. Flagstone varies from 57 to 92 percent of the annual sandstone production. On average, flagstone was 73 percent of dimension sandstone production from 1951-1980. However, this average percent may be too large because production of sandstone for ashlar was greater prior to 1951. Keith (1969e) estimated that the production of good dimension sandstone of all types from pre-1900 up to 1966 totals over 320,000 mt.

The estimated production based on U.S. Bureau of Mines data for the period 1952-1966, is 160,000 mt as flagging and 60,000 mt as other types of dimension sandstone. Therefore, dimension stone production plus flagging production for this time interval is 220,000 mt. Subtracting this total from Keiths (1969) estimate from pre-1900 to 1966, leaves a balance of 100,000 mt of good dimension sandstone of all types produced in Arizona from pre-1900 to 1951. Of this tonnage, about half, or 50,000 mt, is estimated to be flagging production. Considering this and other factors, the best total estimate of flagstone production from pre-1900 to 1991 is about 260,000 mt.

The Coconino Sandstone has been the principal source of the flagstone. Other sources included the Moenkopi Formation, which was quarried in large blocks or as ashlars prior to the 1930's for building construction (Keith, 1969e). The Moenkopi does not easily split for flagging.

Ashlar production in Arizona

Whereas flagstone has been produced from the Coconino Sandstone, ashlar has been produced from the Triassic Moenkopi Formation. Most of the production was prior to the 1930's (Keith, 1968e). A basal, massive sandstone has provided the best material. It consists of a "poorly to well-sorted, fine to very-fine grained, lenticular bed, 20 to 40 feet thick" (Keith, 1968e, p. 447). This massive sandstone contains about 80 percent silica, up to 4 percent iron and aluminum oxides, and 13 percent calcium carbonate (Keith, 1968e). Although the stone forms solid blocks for use in buildings, it does not retain sharp lines and angles (Burchard, 1914). The crushing strength of the material was reported by Kiersch (1955) to between 5,100 and 17,000 PSI (360 and 1,200 kg/cm^2) based on seven fine-grained, well cemented samples. The average crushing strength was about 14,000 PSI (980 kg/cm^2). These samples were collected in the Navajo-Hopi Indian Reservations and may not be representative of the Moenkopi Formation in the KNF.

Geology

Although a range of lithologies may be considered as a source of flagging, the rock must have fissility (be split easily). Lithologies can include slate, sandstone, and schist. Slabs should be between 6-10 cm thick. Winkler (1973) notes that bedding thickness is related to the proportions of clay, silica, and lime. Thickness increases with silica content under conditions of constant lime; thickness decreases with increasing clay. Cross-bedding surfaces may also be used in splitting. Flagstone in the United States (Power, 1983) is generally most acceptable between 1-3 inches thick (2.5-6.7 cm) although thinner material can be used on an extremely firm base or under conditions of light traffic. While bedding thickness may dictate slab thickness, not all bedding planes may split during quarrying and this will produce thicker slabs containing more than one bed.

Clasts include rock fragments and mineral grains. Minerals found in flagstones include quartz, feldspar, mica, garnet, magnetite, hematite, goethite, zircon, calcite, dolomite, and clay. The most desirable clasts in flagstone are fine to medium sized; size uniformity is highly desired.

Although carbonate cement is physically strong, it is subject to chemical attack, an important factor for consideration in many urban environments. Cement effects (1) density, (2) porosity, (3) hardness, (4) toughness, and (5) durability of stone (response to weathering). The best cement is silica. Excessive mica, iron oxide, and clay are all detrimental. Ferric cement is stronger than ferrous cement (Keith, 1969e).

The Coconino Sandstone is generally considered to be the best quality sandstone for flagging found in northern Arizona (Keith, 1969e). The Coconino Sandstone is capped with the Kaibab Formation or Toroweap Formation and rests on either the Hermit Shale or Schnebly Hill Formation (Thiessen, 1986). The Coconino Sandstone is of Permian age and eolian in origin; compositionally it is a quartz arenite with very fine- to medium-grained (0.125-0.25 mm), well-rounded quartz, cemented with silica (McKee, 1979; Blakey and Middleton, 1983; Keith, 1949). Data compiled by H.W. Pierce and reported in Kiersch (1955) suggest that the Coconino Sandstone contains 85 to 90 percent quartz, 5 to 7 percent feldspar, 5 to 7 percent clay plus mica, 2 to 3 percent calcite, and 1 to 2 percent iron oxides. A trace of heavy minerals was noted. Layers along which splitting occurs are either clay-sericitic band, or bands of opaque minerals intermixed with associated alteration products (Kiersch, 1955). Fryberger and Schenk (1988) found that pin stripe laminations in eolian sediments are the result of silt and fine sand deposited in troughs of advancing wind ripples and are subject to cementation before other parts of the unit.

The crushing strength of the Coconino Sandstone as reported by Kiersch (1955) based on data compiled by H.W. Pierce, is 13,000 PSI (910 kg/cm^2) for one medium-grained, well cemented sample. The compressive strength varied between 2,200 and 13,000 PSI (150 and 910 kg/cm^2) based on seven samples. The average was 5,400 PSI (380 kg/cm^2). An average apparent porosity of 8.0 was calculated by dividing the water weight (in grams) absorbed by the volume of sample (cm^3) base on data compiled by H.W. Pierce reported in Kiersch (1955). How applicable the results from these samples of the Coconino Sandstone are to outcrops in the KNF is not known because the samples analyzed were collected in the Navajo-Hopi Indian Reservations.

Definition of permissive areas

Geologic criteria

All outcrops of the Coconino Sandstone and the Sycamore Pass Member of the Schnebly Hill Formation (Blakey and Knepp, 1989; Lehner, 1958) in the KNF are permissive for flagstone. Most of the outcrops are found in the Williams District (fig. 12, tracts FC-4 to FC-6), but small outcrops are also found in the Chalendar District (FC-6) and the North Kaibab District (FC-4 to FC-6; fig. 13). Other variables which are important in target area definition include bedding thickness, extractability, color, accessibility, etc. Outcrops of the Moenkopi Formation in the North Kaibab District (Tracts FM-1, FM-2; fig. 13) and Tusayan Ranger District (Tracts FM-3 to FM-5; fig. 14) are permissive for ashlar.

Outcrop slope criteria

One way to reduce the size of the permissive area for flagstone is using outcrop slope angles. Flagstone quarrying, in or adjacent to, the KNF is sensitive to the type of exposure that the Coconino Sandstone and Schnebly Hill Formation has at the surface. Many outcrops form steep cliffs which apparently do not apparently permit economic mining. However, where the outcrop is a gently sloping surface, economic quarrying apparently can be done.

In order to determine which outcrops are too steep, the slope was measured on 1:24,000 topographic maps at 384 identified flagstone quarries found in both the Ashfork area and the Drake area (fig. 12; tract FS-5). Slope estimates were usually made using elevation data 350 ft above and below the quarry site. Slopes were not measured if the quarry was located at major slope change or in an arroyo. Slope angles in the Drake area were found to be significantly different from both normal distribution and lognormal distribution (at the 1-percent level) using the skewness and kurtosis goodness-of-fit tests (Rock, 1988). Slope angles in the Ashfork area were found to be significantly different from normal distribution but not the lognormal distribution (at the 1-per-cent level) using the skewness and kurtosis goodness-of-fit tests (Rock, 1988). In general, slope angles, as found in this data set, are not sufficiently well behaved to allow valid models to be developed.

On average, much steeper slopes are worked in the Drake area compared to the Ashfork area (fig. 15). Quarries in the Drake area have a median slope of 14 degrees; the median slope in the Ashfork area is half this at 7.2 degrees. The maximum slope likely to be quarried in the Drake area is 33 degrees; in the Ashfork area, the maximum slope is 28 degrees. One quarry in the Drake area was located on a 40 degree slope, but it was an outlier from the rest of the data and has been rejected for purposes of this analysis. As a rule of thumb, outcrops with slopes greater than 35 degrees can be excluded as sites of future flagstone quarrying, based on these data **and given the same general economic conditions in the future as have** prevailed in the past for flagstone quarrying in the KNF. No attempt has been made in this report to redefine the permissive areas using this slope criterion, but this rule of thumb may be used when considering the possible future uses of specific areas containing outcrops of either the Coconino Sandstone or the Sycamore Pass Member of the Schnebly Hill Formation.

Known flagstone and ashlar quarries

Most flagstone quarries in the KNF are shallow, the deepest being 40 ft (12 m) (Scott, 1992). Many operators have extracted flagging out of quarries extending only several feet (a meter or two) below the surface. Most of the future production can be expected from extensions of existing quarries in three dimensions. As the value of the material increases or easily quarried outcrops become exhausted, less suitable outcrops will be worked. Quarrying activities can be so selective that in some cases only outcrops with bedding dipping down slope are worked and where slab extraction and waste disposal is assisted by gravity. Kiersch (1955, p. 65) noted that three factors control quarry practice--"(1) attitude of the cross-stratification, (2) nature of the exposure... and (3) the continuity of cross-strata trends."

Quarries are grouped on 1:24,000 scale topographic maps where conditions of exposure and suitable material in the Coconino Sandstone are optimal. Two areas of past and current activity are identified: the Ashfork area north and northeast of the town of Ashfork in the northwest part of the Williams Ranger District; and the Drake area north of the town of Drake along the southwest margins of the Williams Ranger District (fig. 12).

The discussion on Coconino Sandstone is generally applicable to outcrops found in the Ashfork area (tract FS-4, fig. 12) which is the primary production area for flagstone in the KNF. Flagstone production for the Drake area exploits not only the Coconino Sandstone but also the Schnebly Hill Formation which grades upward into and commonly intertongues with the overlying Coconino (Blakey and Knepp, 1989). Crossbedding continues between the two formations, but the generally buff colored Coconino Sandstone (with occasional grayish orange and yellow) gives way to the pale to moderate red and lavender of the Sycamore Pass Member of ***the Schnebly Hill Formation (Blakey and Knepp, 1989; Lehner, 1958). Some*** of the colored material (reds and purples) is in the Coconino Sandstone where it is intertongued with the Schnebly Hill Formation. Cross-beds are usually between one to eight inches thick, but are occasionally thicker in the Drake area. It is quite likely that much of the production reported by Lehner (1958) was from the Schnebly Hill Formation. Flagstone production in the Drake area, as described by Lehner (1958), was based on the following attributes: (1) thin lamination (one to three inches), (2) ease of splitting, and (3) colors in demand at the time. At the time of the Lehner (1958) study, colors in demand were red, lavender, and yellow.

In the Drake area (tract FS-5, fig. 12), site preparation for flagstone quarrying involved removal of overburden, usually by hand but sometimes using bulldozers. Lehner (1958) noted that flagstone extraction was inherently wasteful. Flagstone was extracted from open-pits where holes were drilled six to eight feet back from the quarry face and were filled with explosives for blasting. Individual layers were separated or lifted using wedges. Sheets sold as flagstone had to be a minimum of 18 inches (46 cm) on a side; most were around 4 to 6 square feet (0.4 to 0.6 m^3). Those layers greater than two inches (5 cm) thick (called cutting stone) were used for building purposes (exterior decoration, veneers) and would be subsequently cut into strips two to four inches (10 cm) in thickness and about 3.5 inches (9 cm) wide. Occasionally larger blocks were produced at quarries as building blocks (ashlar). Around 1958, flagstone from the Drake area sold for $12 per short ton ($13 per mt); cutting stone sold at $6-8 per short ton (7-9 per mt) as reported by Lehner (1958). The crushing strength of the material is reported by Kiersch (1955) to be 7,200 PSI (510 kg/cm^2) based on one medium-grained slightly weathered sample. The quarried area extends south for some distance into the Prescott National Forest.

No quarries for ashlar are identified in the Moenkopi Formation in the North Kaibab Ranger District (fig. 13)

MODELS FOR FLAGSTONE

Introduction

Develoment of models for flagstone were attempted to describe the **extent and magnitude of quarry activity for flagstone present in the** Coconino Sandstone and Schnebly Hill Formation. No attempt was made to model ashlar in the Moenkopi Formation. Extraction of flagstone is sensitive to a large number of variables including depth, thickness, color, fashion, etc. Because flagstone is a high volume, low value commodity, only surface deposits can be worked. Therefore all flagstone deposits (1) must be exposed at the surface and (2) can only be economically worked to a shallow depth (but as of this time, an unknown depth). Scott (1992) suggests that depths do not exceed 30 ft (9 m). The Coconino Sandstone exposed in cliffs is unsuitable and cannot be worked economically. Permissive areas include the Coconino Sandstone in the Ashfork area, where outcrops have low surface slopes.

The value of flagstone quarries is predominantly derived from the production of flagstone, but it also can include byproduct stone used in ashlar and other construction material. However, the value of the flagstone is usually much greater than the byproduct stone so it is the suitability of the deposit for flagstone that is the defining factor. Therefore, the material must be suitably thin (2-3 inches or 5-8 cm). The Coconino Sandstone has varying thickness of bedding, some of which is more suitable than others. Ease of flagging extraction is also related to bedding thickness. Sufficient moisture in the stone is desirable since it allows for easy splitting. While some type of rough guide can be developed for speculating on suitable bed thicknesses, flagstone aesthetics of flagstone (color, etc.) is highly unpredictable over any long time period.

Model development was encumbered by the fact that production data from individual quarries is not commonly available. Even if production data is available, reserves are not estimated, and no precise depths or range of depths are available. Flagstone quarrying has been done for nearly one hundred years in the KNF. The quarry represents a combination of economic and geologic conditions. Inspection of topographic sheets of areas both inside and adjacent to the Williams and Chalendar Ranger Districts suggests that there are at least 400 quarries in the Coconino Sandstone or Schnebly Hill Formation. Both Bill Scott of the U.S. Bureau of Mines, Denver (oral commun., June 16, 1992) and Nyal Niemuth of the Arizona Department of Mines and Mineral Resources, Phoenix (oral commun., ***June 16, 1992) agreed that there are likely to be twice as many, or 800*** quarries in the two formations in and adjacent to the Williams and Chalendar Ranger Districts. Neither the flagstone deposits nor the the quarries used to work the deposits can be successfully modeled. Therefore, predictions need not be made concerning the numbers of areas where future quarrying might be expected in the future. The model, even for quarries, is imprecise and requires several definitions and standardized procedures.

Target-area model

The quarried target area is the size of the area containing one or more sandstone quarries that are separated by a distance equal to or less than 0.5 km (0.31 mi) as measureed on 1:24,000 scale maps. The quarried-target-area model (fig. 16) is based on data from 29 quarried-target areas with two or more quarries. This model is applicable to 60 percent of the deposits; otherwise the deposit has a single standard quarry and a default area of 0.37 ha. This is the minimum area needed to show a quarry symbol on a 1:24,000 scale map. The distribution of quarried-target-areas for two or more quarries was found to be significantly different from the lognormal distribution (at the 1-per-cent level) using the skewness and kurtosis goodness-of-fit tests (Rock, 1988). While statistically unsatisfactory, the model still gives an estimated range of sizes of an undiscovered quarried target area. The model is crude because it contains not only the area of the quarries proper but also unworked areas between quarries. The target-area model is partly an artifact of the procedure used, but it gives a clue to the sizes of target flagstone deposits present in the region.

One complication is that 40 percent of the target areas contain just a single standard quarry, and therefore each area is set equal to 0.37 ha by definition. Therefore, 40 percent of the deposits are represented by a single standard quarry. Considering both the single quarry deposits and the **cluster of quarries, the median quarried target area is about 2.6 ha. The** development of a better model may be desirable, but,given the lack of quarry descriptions and data on spacing between quarries, this one is currently the best.

Estimate of numbers of undiscovered flagstone deposits

A strategy to estimate the number of undiscovered flagstone deposits is not yet in hand. While all outcrops of the Coconino Sandstone and the Sycamore Pass Member of the Schnebly Hill Formation in the KNF are clearly permissive, only selected parts have been quarried. The situation is identical for the Moenkopi Formation as a source of ashlar.

Improving flagstone assessment

A better assessment of flagstone resources could be made given an inventory of quarries and prospects. This is highly recommended before another assessment of flagstone resources in the KNF is attempted. Useful data include the location, the area, and average depth. These data could be used to develop better models. Even this would only give a sense of produced flagstone because reserves are a function of depth, but some valid estimates might be possible.

An inventory of prospects can assist in the estimate of the number of undiscovered deposits. It is unlikely that the few flagstone prospects shown on the 1:24,000 maps (or air photographs) are representative of the number of prospects actually present, considering that only half of the suspected flagstone quarries are shown.

Better targeting criteria is needed that can help in the estimate of the number of undiscovered deposits. Flagstone quarries are not randomly distributed, but some types of stratigraphic controls within the Coconino Sandstone appear to be present. For example, quarries appear to be more numerous near the top of the formation in the Ashfork area (fig. 17). In this case, elevation is used as an approximate estimate of stratigraphic position. No correlation was found between elevations and slope angles, suggesting that a quarry's location is dependent on some desirable quality of the sandstone. For example, quarries may be preferentially located **where better parting surfaces (the result of thicker layers of fine sand and** clays between the bedding' planes of the sandstone beds) are common. It seems that the upper part of the Coconino Sandstone was deposited with more silt or fine sand than is typical of the rest of the unit. This may indicate an overall atmospheric change in which additional wind-carried dust and silt was deposited in the area.

A study of the Coconino Sandstone in the areas both with and without flagstone quarries is highly desirable in subsequent assessments. The use of elevation as a proxy for strategraphic position needs to be checked. Houser (written commun., May 24, 1993) suggests that faults with small displacements of 50 to 100 ft are common, they may not be shown on geologic maps, and that elevations will have little relation to stratigraphic position within just a few miles. Other factors that need to be evaluated in the distribution pattern of quarries include climate control (e.g., freeze/thaw cycles, snow cover), and ground water control of bedding plane fissility (Brenda Houser, written commun., May 24, 1993).

MISCELLANEOUS NON-METALLIC DEPOSIT TYPES

Sand and Gravel

Scott (1992) reports that little sand and gravel is identified in the KNF. What sand is available is in stream beds, which lack gravel however. This has led to the substitution of volcanic cinder and scoria.

Sources of other construction material

In addition to formations identified previously, the Supai Formation, consisting of siltstone and sandstone beds, may be a source of small size riprap. The Supai Formation in the North Kaibab Ranger District is delineated in fig. 18.

MINERAL RESOURCE ASSESSMENT OF SOLUTION-COLLAPSE BRECCIA PIPE URANIUM DEPOSITS

By James D. Bliss and Charles T. Pierson

Geology

To date, the Colorado Plateau is the only region where solution-collapse breccia pipe uranium deposits have been identified. Both deposits and associated geology have been subjected to intense study (see Van Gosen, and Wenrich, 1989; Wenrich and others, 1988, 1989; Wenrich, 1985). In brief, deposits occur in solution collapse structures that are the result of upward stoping from caves developed in the Redwall Limestone. Pipes can extend upward for more than 1000 feet (300 m) (Finch, 1992) passing through the overlying Pennsylvanian, Permian, and Triassic rocks. Pipes are between 30 -175 ft (9-51 m) in diameter (Finch, 1992). Initiation of upward stoping apparently is less common if the Redwall Limestone is less than 50 ft (15 m) thick. Mineralized pipes are commonly found adjacent to the Supai Formation, the Hermit Shale, and the Coconino Sandstone (Finch and others, 1990); for most areas mineralization is at a depth of 500-2000 ft (150-600 m) below the surface.

Previous assessments

The United States Geological Survey, in accordance with a Memorandum of Understanding, dated September 20, 1984, between the U.S. Department of Interior and the U.S. Department of Energy, provided an estimate of undiscovered uranium endowment in solution-collapse breccia pipe uranium deposits in the Grand Canyon region of northern Arizona and adjacent Utah (Finch and others, 1990). The method or deposit-size-frequency method (DSF, option C) used to make this assessment was a modification of one developed for NURE (National Uranium Resource Evaluation) as described by Finch and McCammon (1987). The methodology used the Hack-Pinenut area (which is just off the western edge of the North Kaibab Ranger District, KNF) as a control (Finch and others, 1990). The Hack-Pinenut area is found on the north side of the Grand Canyon National Park (fig. 19).

An assessment of undiscovered uranium endowment in solution-collapse breccia pipe uranium deposits in KNF can be made using Finch and others' (1990) favorable areas classification scheme. The elicitations by a principal scientist in the previous assessment (as required to make a DSF, option C type assessment) are used here as well. The only modification needed for the Grand Canyon region assessment is an adjustment of the size of the favorable area classes (Finch and others, 1990; fig. 2) to reflect the area of each class that falls within the boundaries of the KNF. Areas used include minor amounts of privately-held and other lands surround by KNF land. The following classification is used for favorable areas:

A--most favorable (excludes Hack-Pinenut control area), capped with Kaibab Formation;

B--less favorable but does contain the full section of Paleozoic formations which host deposits; Redwall Limestone thinner but still is likely greater than 50 ft (15 m) thick; and

D--lower favorability, does <u>not</u> contain the full section of Paleozoic formations that host deposits; but Redwall Limestone likely greater than 50 ft (15 m) thick and comparable to the unit under favorable area type A.

(Area types C and E, used in the assessment of the Grand Canyon region are not found in the KNF and need not be discussed.)

Areas covered with basalt include class B. For example, magma rising to the surface and forming larger cones and vents of the San Francisco volcanic field may have destroyed any deposits nearby. These areas were excluded from the assessment by Finch and others (1990). However, some areas were simply covered with volcanic material that would hide the deposits and make them difficult to detect even using existing geophysical methods (Finch and others, 1990). The assessment by Finch and others (1990) included areas with basalts from 5 ft (1.5 m) to 300 ft (90 m) thick, although they clearly stated that most of these deposits were "essentially nonviable resources under present conditions" (Finch and others 1990, p. 12). Also see Finch and others (1990) for a full discussion of favorable areas criteria found outside the KNF.

Using the same input variables used by Finch and others (1990), but with modified area class size, the probability distribution of undiscovered uranium endowment can be calculated using the TENDOWG program (McCammon and others, 1988). Five separate probability distributions are calculated--by the three separate sections of the KNF (North Kaibab Ranger district, Tusayan Ranger district, and the adjoining Chalendar and Williams Ranger districts) and by favorable area type therein if applicable.

Favorable area types in ranger districts

North Kaibab Ranger District

About 97 percent, or 258,000 ha (994 mi^2) of the North Kaibab Ranger district (fig. 20) is in the most favorable area A, which extends outside the ranger district to the east, north, and west. The Hack-Pinenut control area lies just to the west of the North Kaibab Ranger District of which 1,000 ha (4.1 mi^2) is within this part of the KNF (0.4 percent). About 2.6 percent or 6,909 ha (26.7 mi^2) of the ranger district is in the lower favorability area D, which extends outside the ranger district to the west and southwest and extends into the Grand Canyon National Park to the south and west.

Tusayan Ranger District

All of the Tusayan Ranger district of 133,000 ha (515 mi^2) is in the most favorable area A, which also extends to the east, south, and west of this part of the KNF (fig. 21).

Chalendar and Williams Ranger Districts

About 98 percent or 243,000 ha (939 mi^2) of the combined Chalendar and Williams Ranger districts (fig. 22) is in less favorable area B, which also extends outside the two districts to the east, north, and west.

Parts of less favorable area B are further classified. About 85 percent or 207,000 ha (798 mi^2) of area B is designated as B_b--covered with volcanics and 990 ha (3.83 mi^2) of area B is designated as B_s--covered with Tertiary sediments. A portion of less favorable area B of 35,500 ha (137 m^2) is without further classification. The balance of the area, 4,970 ha (19.2 mi^2)

of the ranger districts contains volcanic conduits, etc. which preclude the presence of undiscovered deposits.

Predicted uranium endowment

Probability distributions of the undiscovered unconditional mean uranium endowment for North Kaibab Ranger District , Tusayan Ranger District, and the combined Chalendar-Williams Ranger Districts are found in table 1. These do not represent additional uranium endowments to those reported by Finch and others (1990) but rather they suggest what portion of that endowment is found within the KNF. The calculation was made using the computer program TENDOWG (McCammon and others, 1988). See Finch and others (1990, tables 1-2) for size-frequency distribution and listing of L factors of favorable areas used in these calculations.

The total mean unconditional endowment of 233,000 short tons (st) (211,000 metric tons (mt)) U_3O_8 for the KNF is 18 percent of the total mean endowment of 1,320,000 st (1,200,000 mt) estimated for solution-collapse breccia pipes in the Grand Canyon Region of Northern Arizona and adjacent Utah (Finch and others, 1990). Most of the undiscovered U_3O_8 endowment in this region for this deposit type is expected to be found in areas outside of the KNF. Of the three units evaluated (North Kaibab District, Tusayan District, and the combined Chalendar-Williams districts), the North Kaibab district is expected to contain approximately **half of the undiscovered uranium endowment (mean of 112,000 st (102,000** mt) U_3O_8) predicted in the KNF. The remaining uranium endowment is almost equally divided between the other two units--57,800 st (52,400 mt) in the Tusayan District and 63,400 st (57,500 mt) in the the combined Chalendar-Williams districts (table 1).

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Table 1. Undiscovered uranium endowment in the Kaibab National Forest, Arizona.

[Values (short tons) of U_3O_8 are rounded to three significant figures. For each each favorable area in a district or district group, the odds are 9 to 1 that the true unconditional endowment in tons of U_3O_8 is between the values given for a probability of 0.05 and 0.95.]

Ranger district(s):	North Kaibab		Tusayan	Chalender and Williams		
Favorable area:	A	D	A	B	B_b	B_s
Probability						
0.05	29,400	101	15,200	2,360	13,700	55.9
.10	40,200	139	20,800	3,240	18,900	90.5
.15	49,000	170	25,400	3,950	23,000	110
.20	56,900	197	29,400	4,600	26,800	128
.25	64,300	223	33,200	5,200	30,300	145
.30	71,500	248	37,000	5,790	33,800	162
.35	78,600	273	40,700	6,380	37,200	178
.40	85,800	299	44,400	7,000	40,600	195
.45	93,200	325	48,200	7,590	44,200	212
.50	101,000	352	52,100	8,220	47,900	230
.55	109,000	380	56,200	8,880	51,800	248
.60	117,000	411	60,600	9,600	55,900	268
.65	126,000	443	65,300	10,400	60,400	290
.70	136,000	479	70,500	11,200	65,400	314
.75	148,000	520	76,400	12,200	71,000	341
.80	161,000	568	83,200	13,300	77,700	372
.85	177,000	627	91,600	14,700	85,900	412
.90	198,000	706	103,000	16,600	97,000	462
.95	232,000	831	120,000	19,700	115,000	551
Mean....................	112,000	394	57,800	9,250	53,900	259.
Mean (by district(s)):	**112,000**		**57,800**		**63,400**	

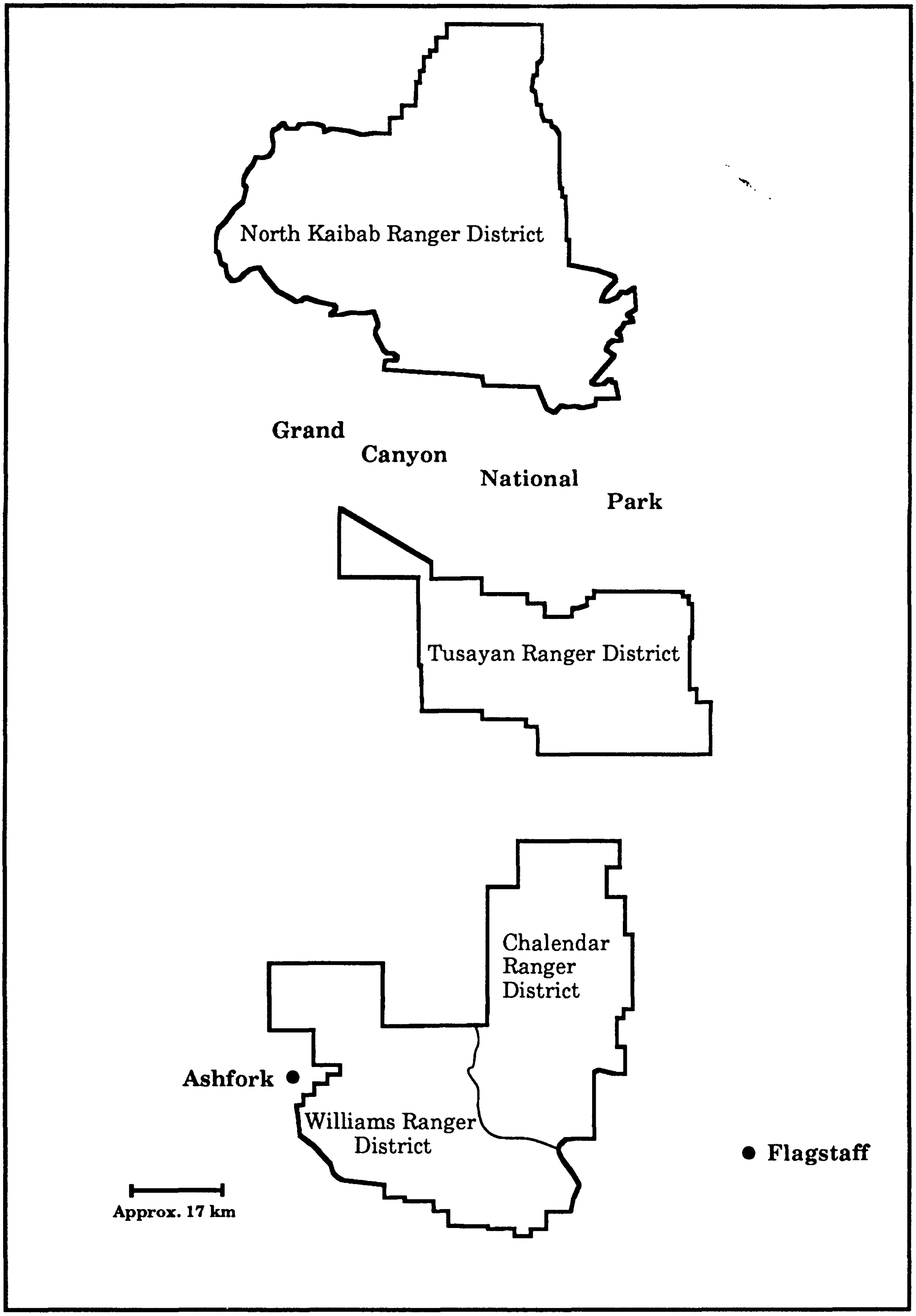

Fig. 1. Location of the four ranger districts of the Kaibab National Forest, Arizona.

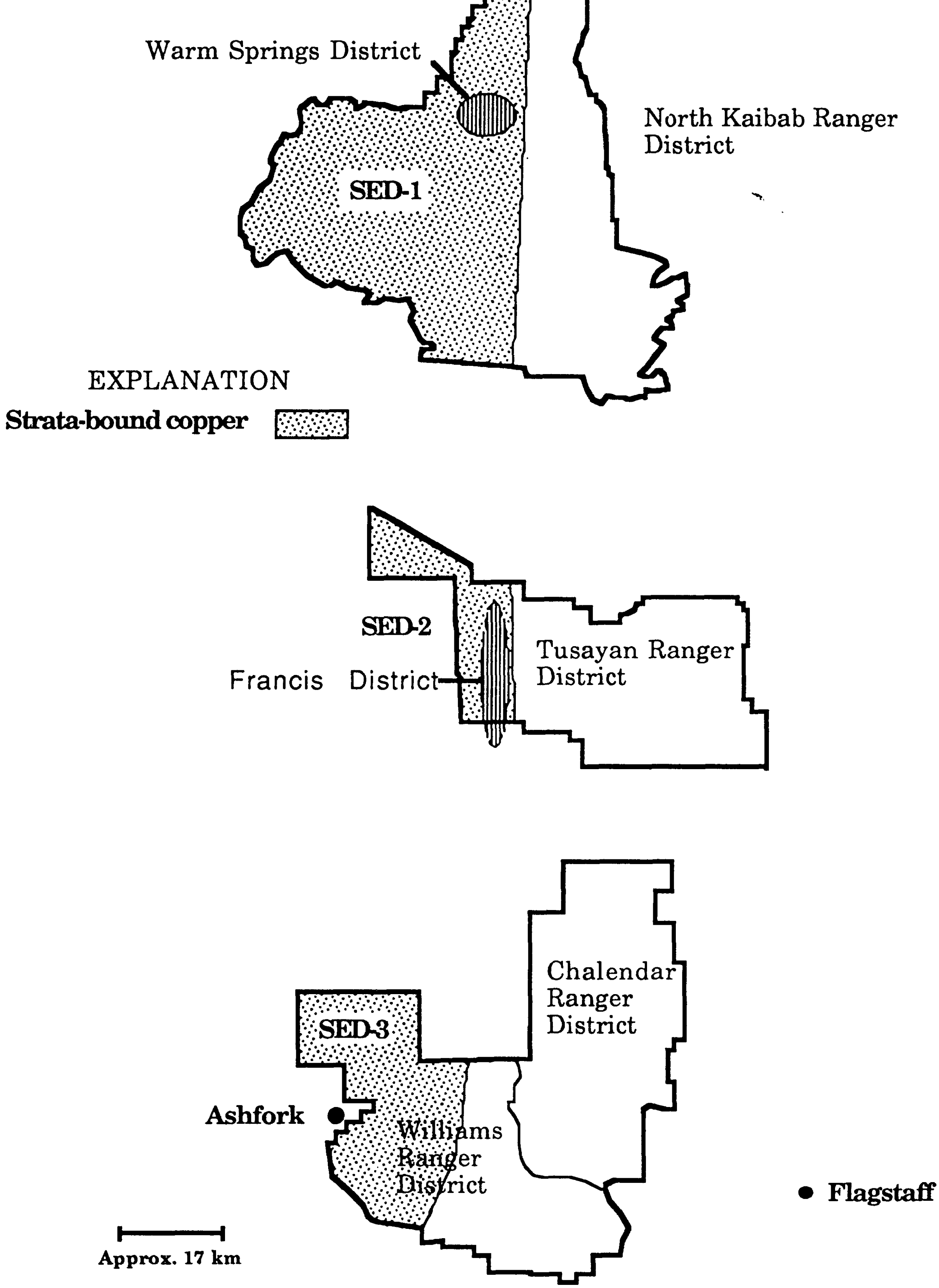

Fig. 2. Permissive tracts for strata-bound copper. Generalized tract boundaries (SED-1, SED-2, SED-3) based on facies change in the Harrisburg member of the Kaibab Formation, KNF, Arizona. Substantial uncertainty in east boundary of SED-3.

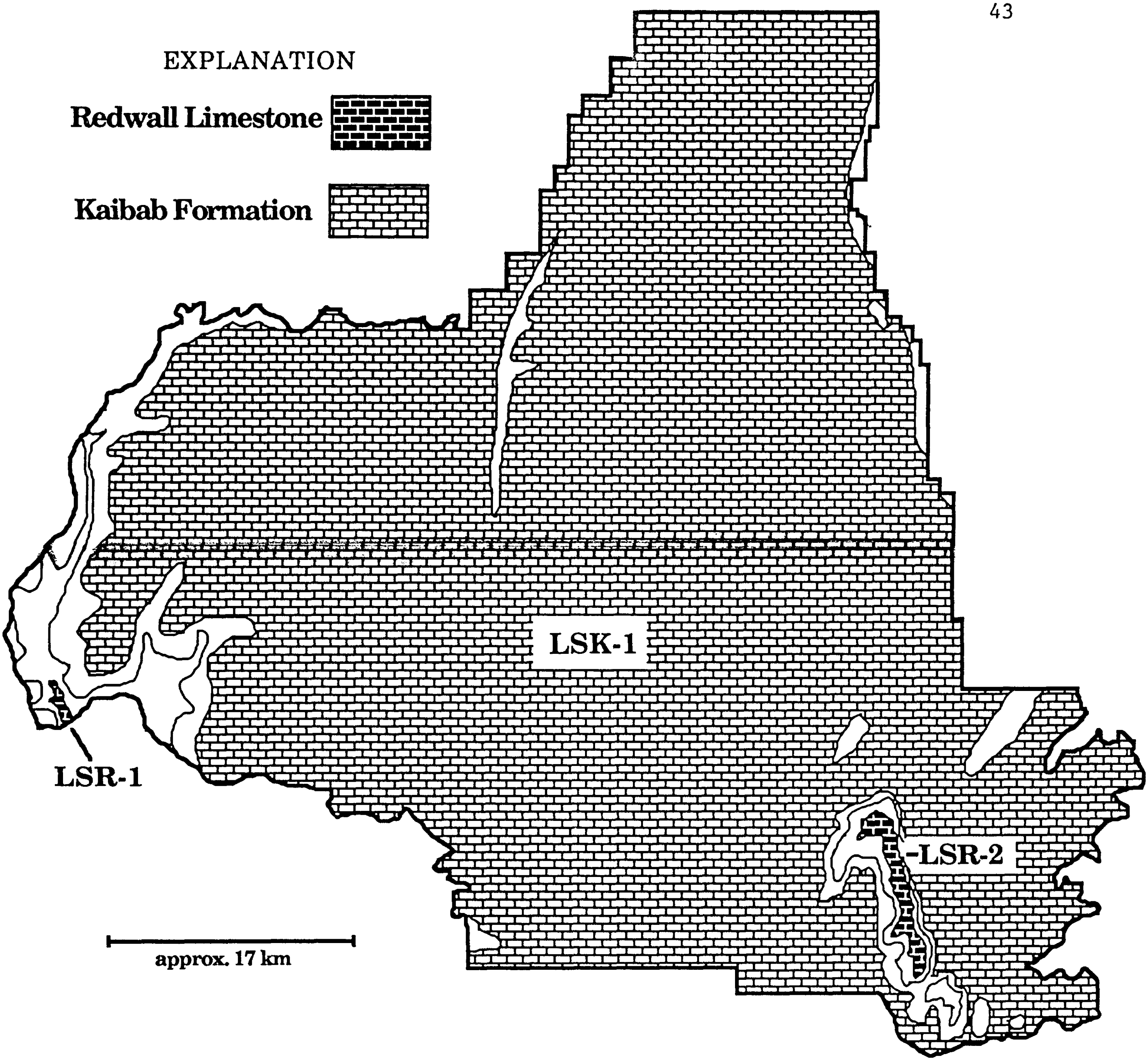

Fig. 3. Permissive tracts for stratiform, replacement and residual manganese deposit types; replacement iron deposits; remnant solution-collapse breccia pipe uranium deposits; and limestone in the North Kaibab Ranger District, KNF, Arizona. Delineation should be exclusive to the Redwall Limestone (Tracts LSR-1, LSR-2) and the Kaibab Formation (Tracts LSK-1) but has included other units due to small outcrop areas at this scale. The Kaibab Formation tract is permissible for stratiform, replacement, and residual manganese deposits; and remnant solution-collapse breccia pipe uranium deposits. Redwall Limestone tracts are permissible for replacement iron deposits. Limestone is permissible in both the Redwall Limestone and Kaibab Formation. See detailed geologic maps of this area or make field checks to determine actual outcrop areas of these two formations.

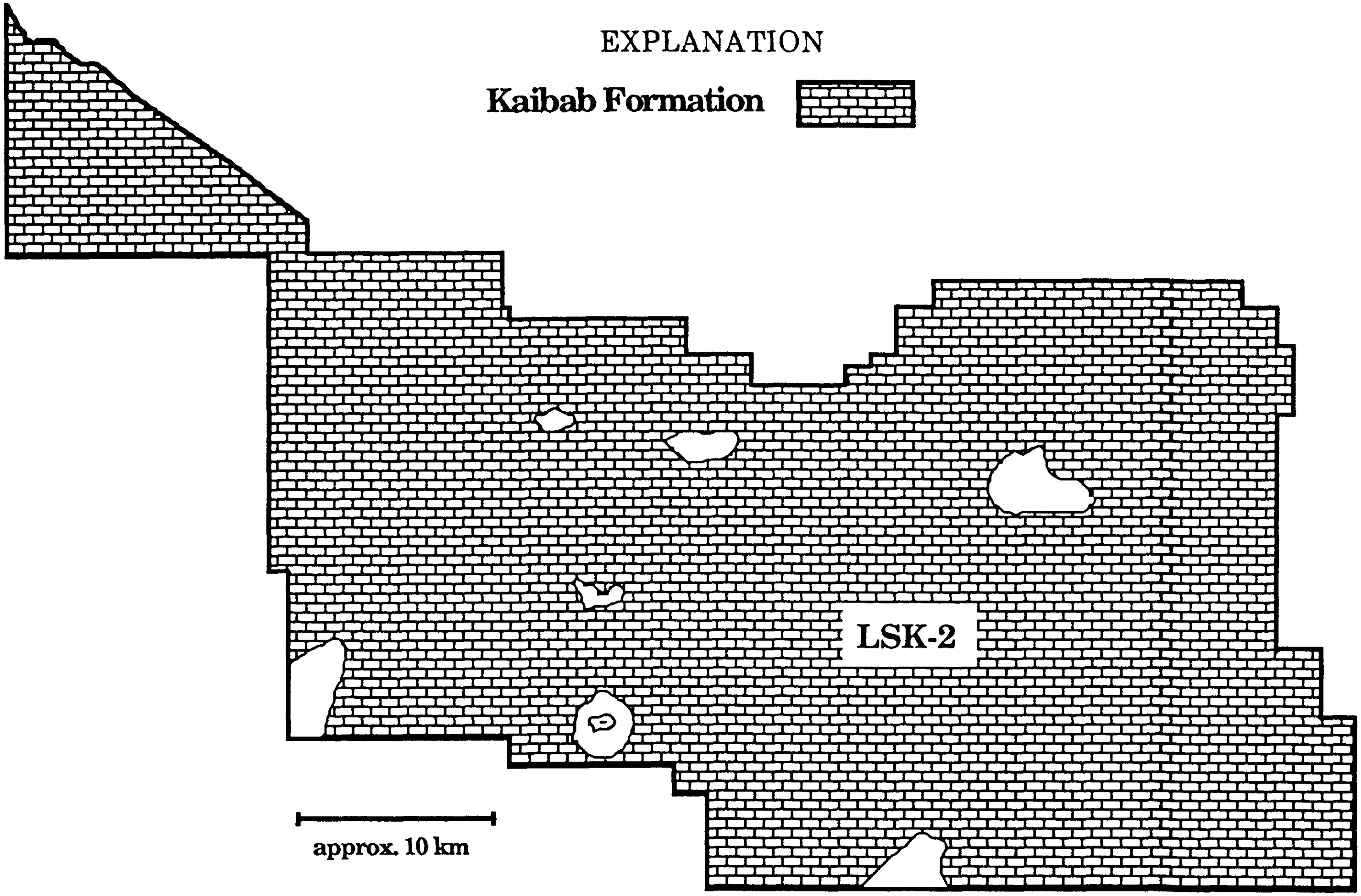

Fig. 4. Permissive tract for stratiform, replacement, and breccia-type manganese deposits; remnant solution-collapse breccia pipe uranium deposits; and limestone in the Tusayan Ranger District, KNF, Arizona. This generalized delineation should be exclusive to the Kaibab Formation (Tracts LSK-2) but may have included other units (or missed some Kaibab Formation) in error. See detailed geologic maps of this area or make field checks to determine actual outcrop areas.

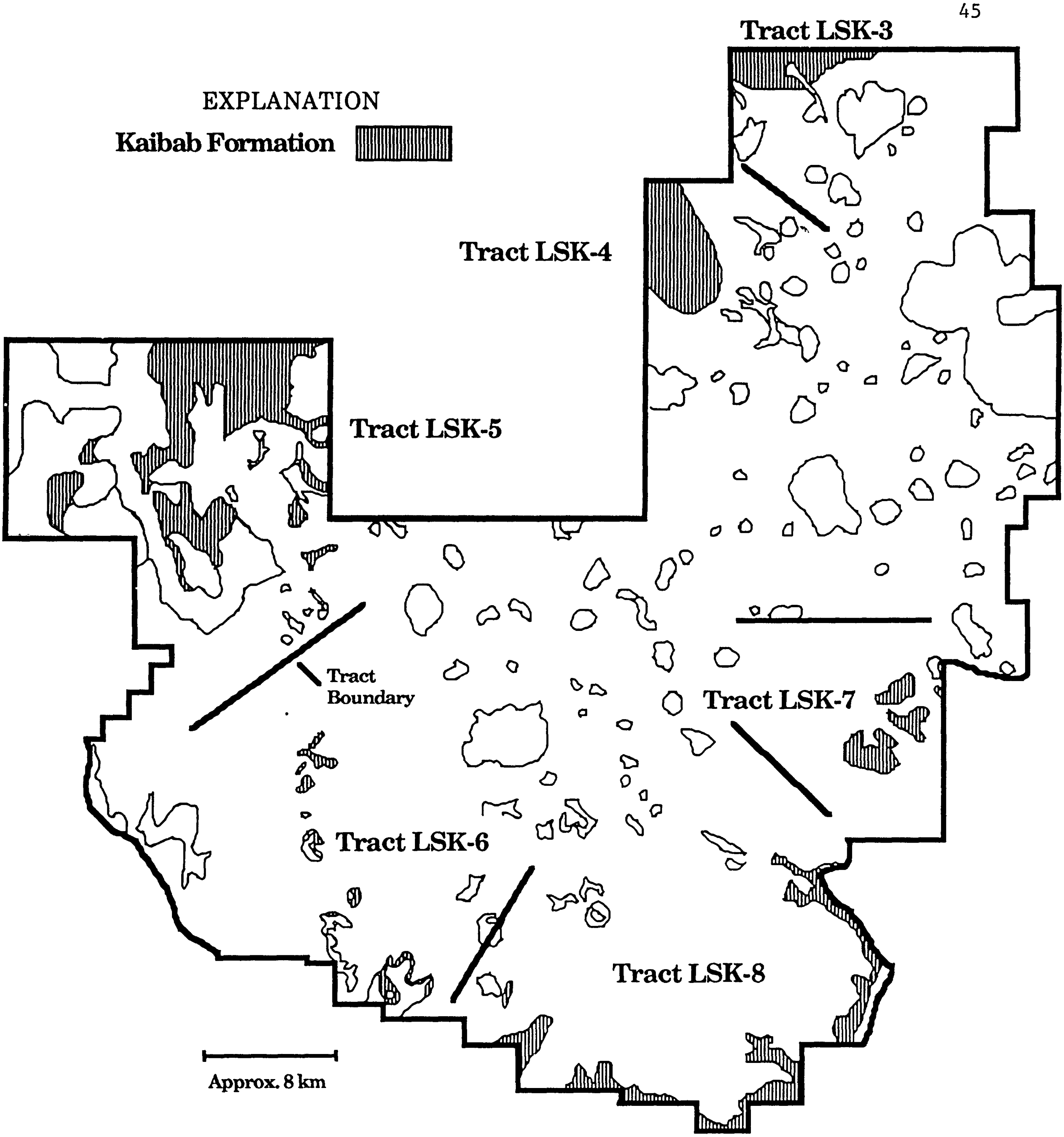

Fig. 5. Permissive tracts for stratiform, residual, and breccia-type manganese deposits; remnant solution-collapse breccia pipe uranium deposits; and limestone in the Williams and Chalender Districts, KNF, Arizona. Delineation should be exclusive to the Kaibab Formation (Tracts LSK-4 to LSK-8) but can only be shown approximately here. See detailed geologic maps of this area or field checking may be necessary to determine actual outcrop areas of the Kaibab Formation.

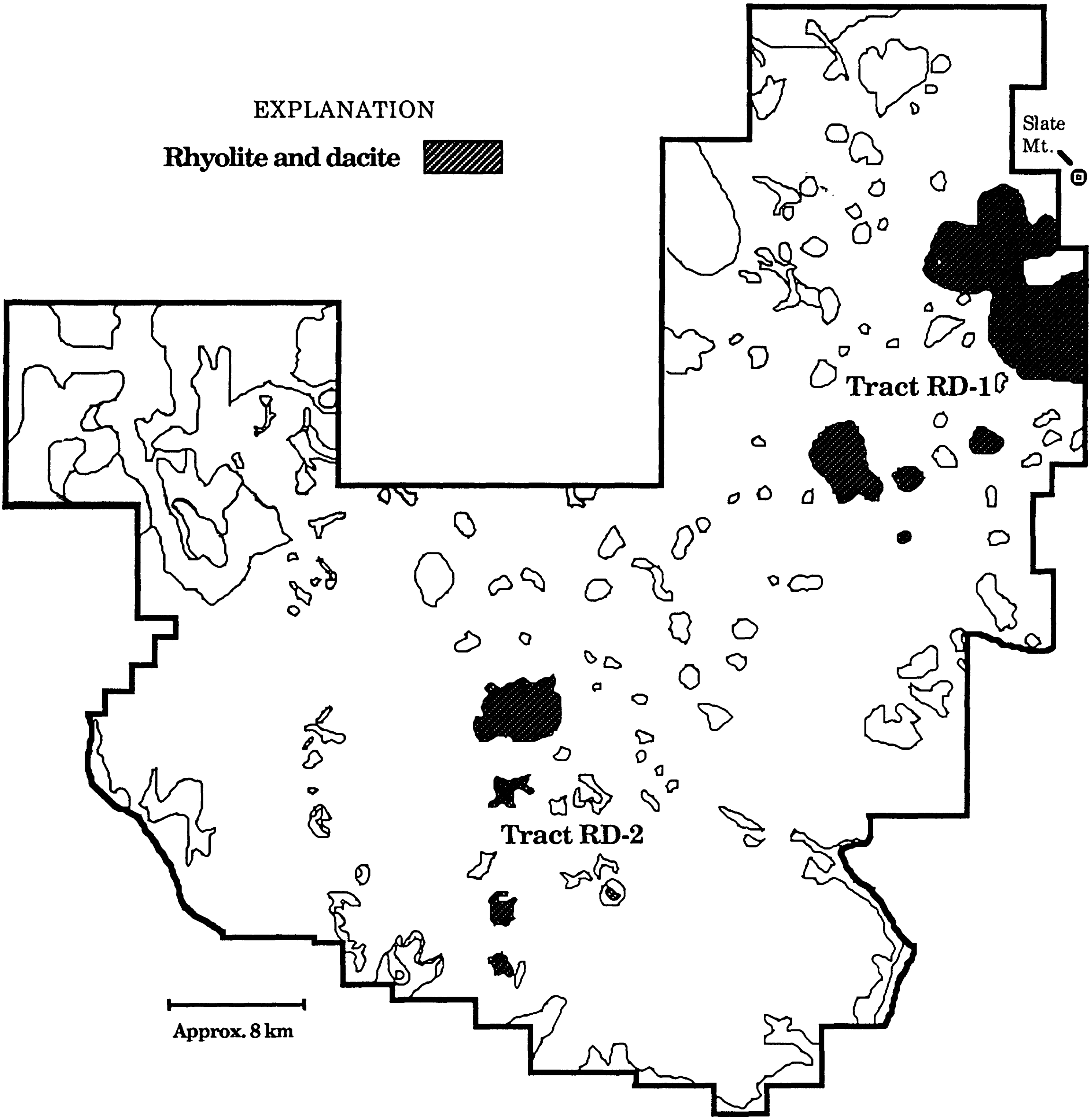

Fig. 6. Permissive tracts for iron veins and pumice associate with rhyolite and dacite rocks in the Williams and Chalender Rangers Districts, KNF, Arizona. Some cinder deposits may be included. Delineation should be exclusive to areas with these lithologies (Tracts RD-1, RD-2) but can only be shown approximately here. See detailed geologic maps of this area or field checking may be necessary to determine actual outcrop areas. Slate Mountain (⊡) is north of tract RD-1 (see "Iron veins associated with rhyolite" in text).

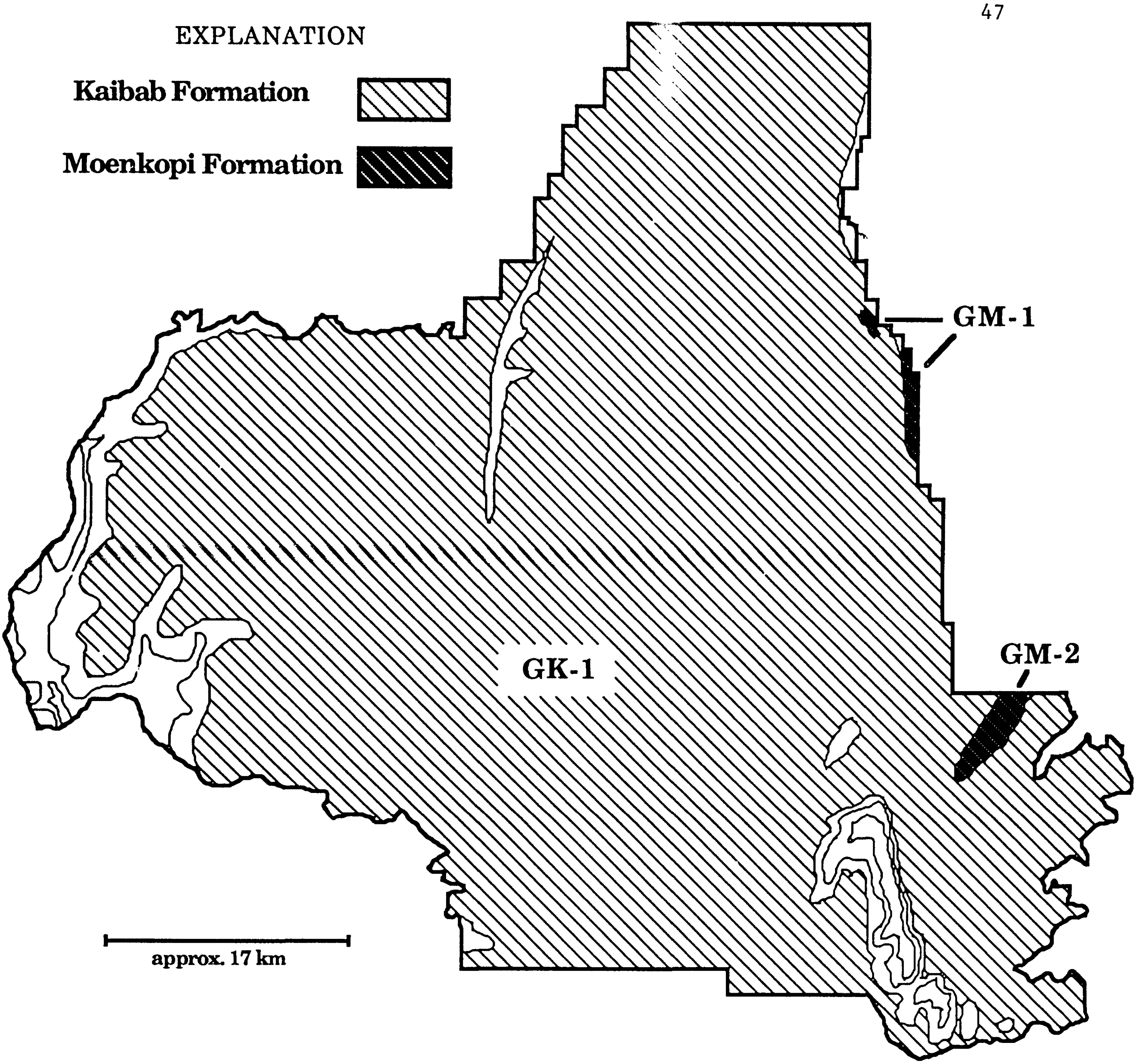

Fig. 7. Permissive tracts for bedded gypsum in the North Kaibab Ranger District, KNF, Arizona. These generalized delineated tracts should be exclusive to the Kaibab Formation (tract GK-1) and the Moenkopi Formation (tract GM-1, GM-2) but may include other units (or missed some part of the indicated formations) in error. See detailed geologic maps of this area or make field checks to determine actual outcrop areas.

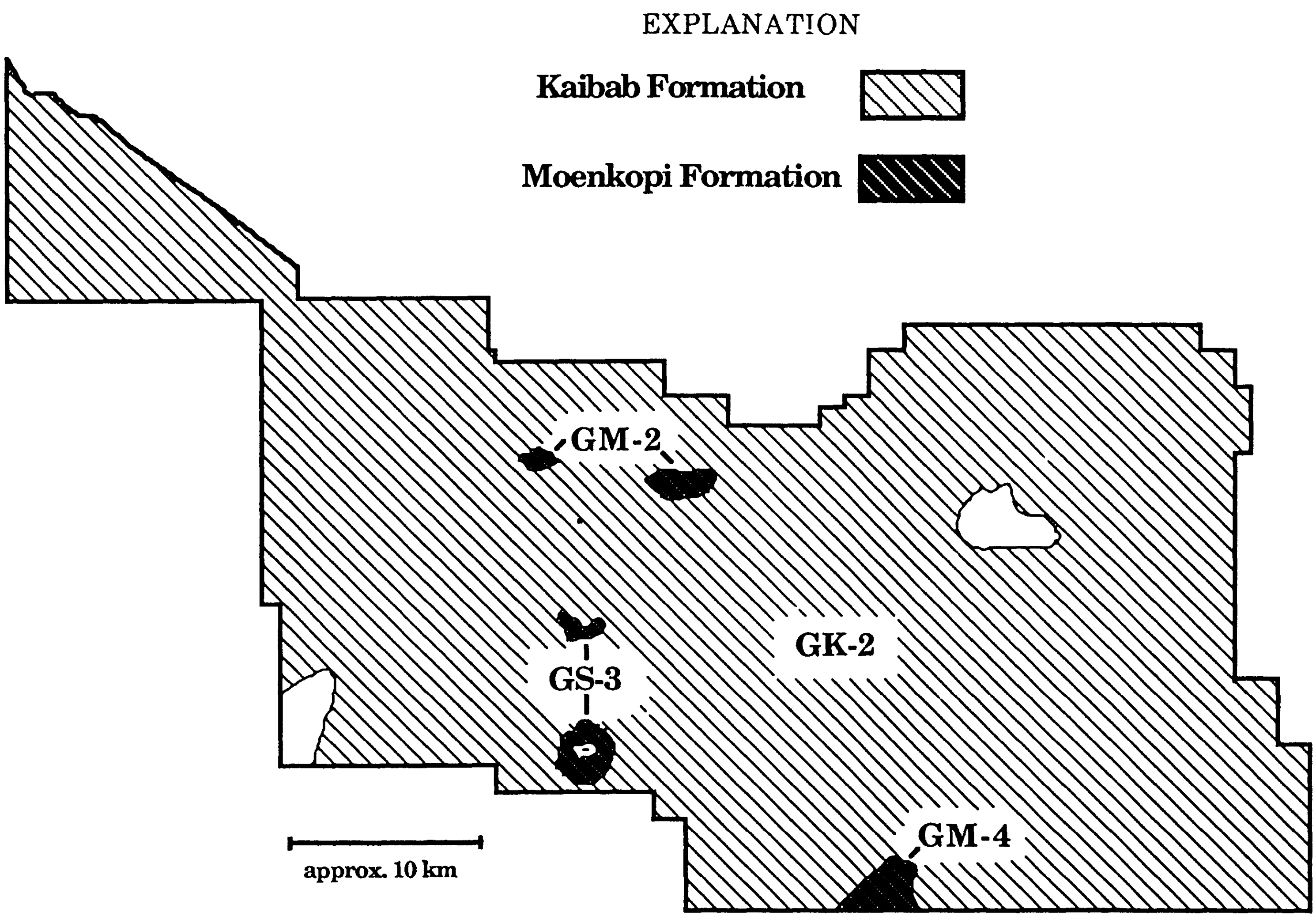

Fig. 8. Permissive tracts for bedded gypsum in the Tusayan Ranger District, KNF, Arizona. These generalized delineated tracts should be exclusive to the Kaibab Formation (tract GK-2) and the Moenkopi Formation (tract GM-3, GM-5) but may include other units (or missed some part of the indicated formations) in error. See detailed geologic maps of this area or make field checks to determine actual outcrop areas.

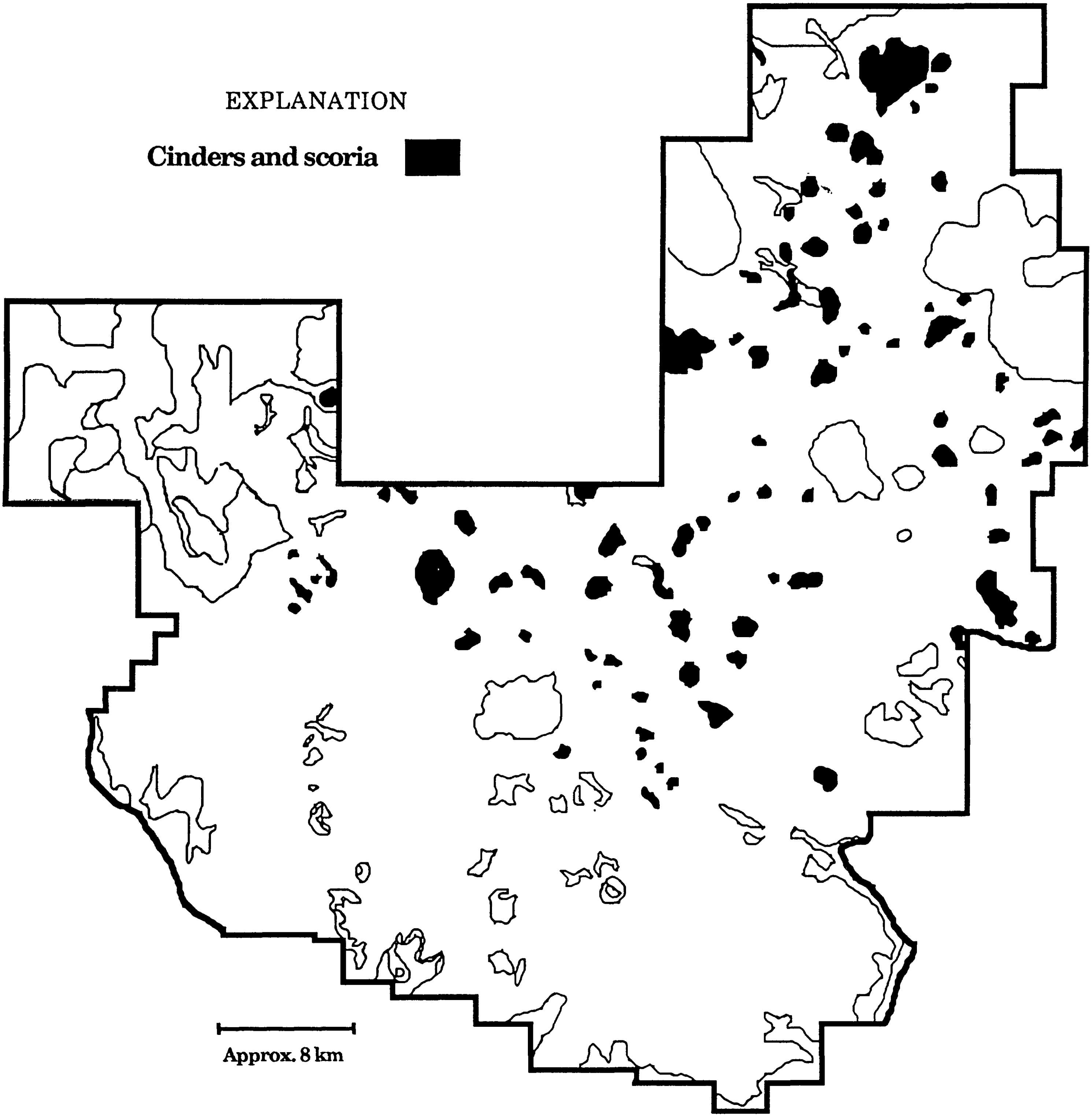

Fig. 9. Permissive tracts (in solid black) for cinders and scoria in cinder cones in the Williams and Chalender Districts, KNF, Arizona. Minor amounts of pumice may also be present. Delineation is exclusive to cinder cones but can only be shown approximately here. Fine-grained material distal to cones is not delineated. See detailed geologic maps of this area or make field checks to determine actual outcrop areas.

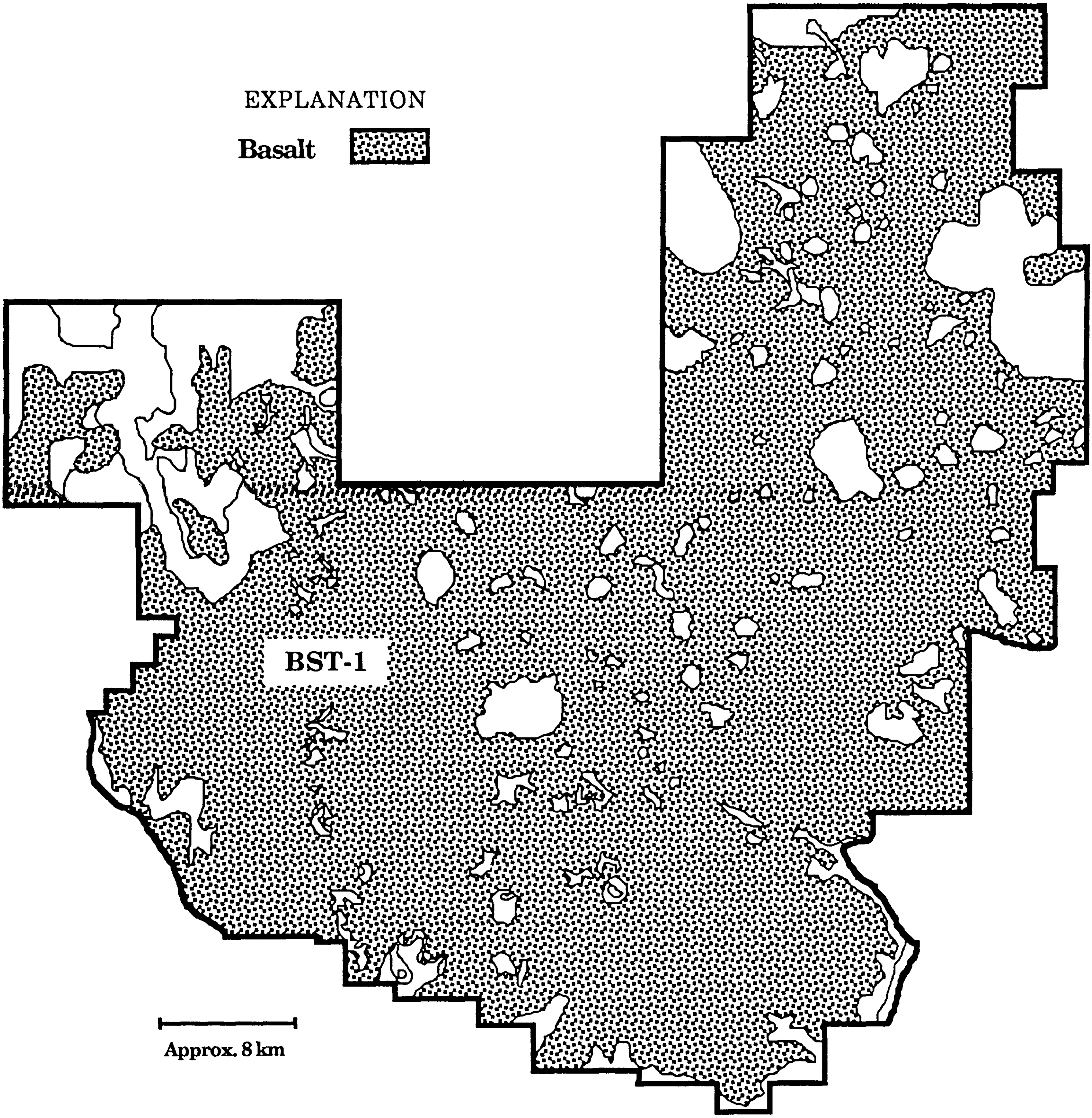

Fig. 10. Permissive tract (BST-1) for basalt in the Williams and Chalendar Districts, KNF, Arizona. Delineation should be exclusive to the basalt (and related volcanic material) but can only be shown approximately here. See detailed geologic maps of this area or make field checks to determine actual outcrop areas.

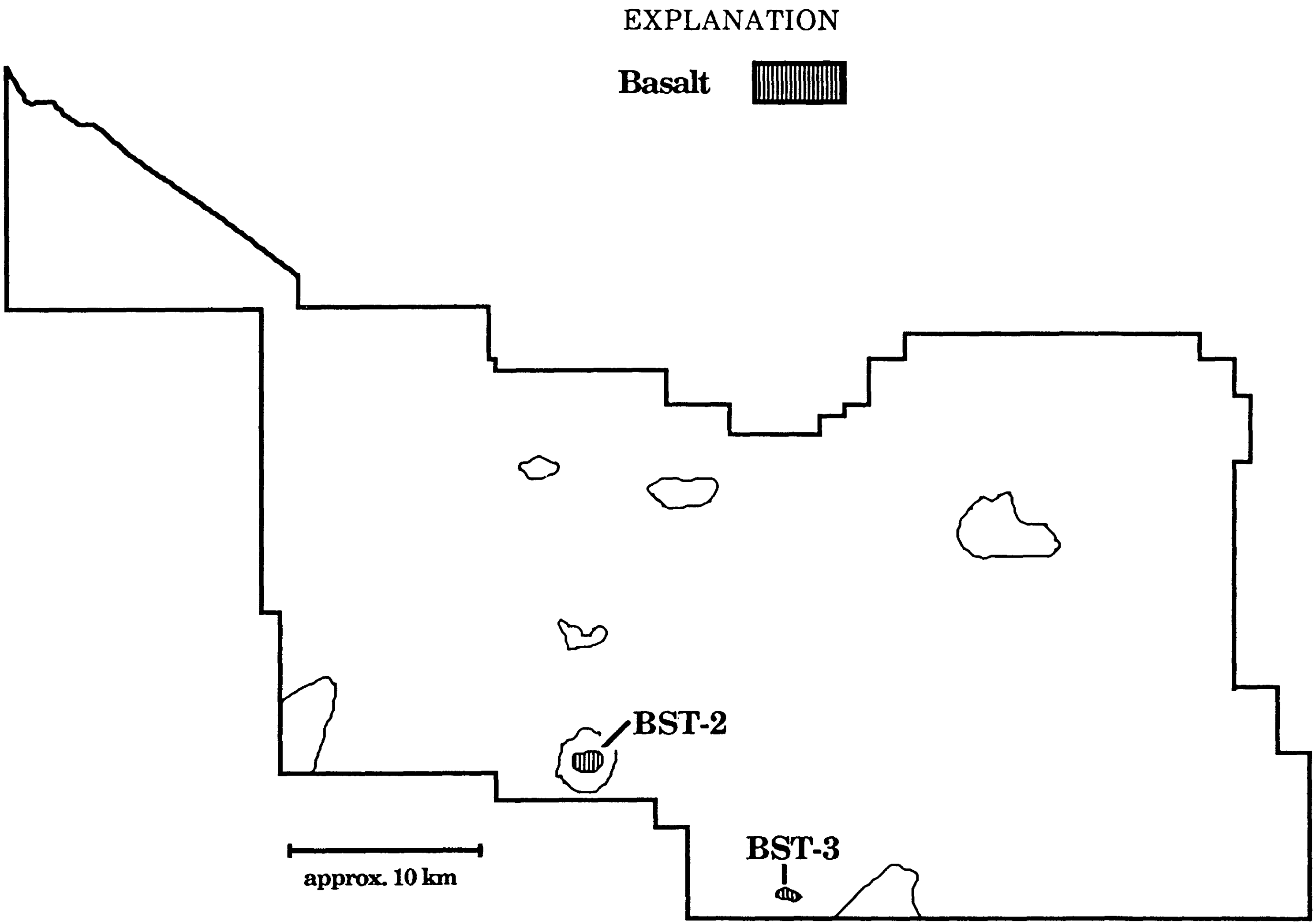

Fig. 11. Two small permissive tracts (BST-2, BST-3) for basalt in the Tusayan Ranger Districts, KNF, Arizona. Delineation should be exclusive to the basalt (and related volcanic material) but can only be shown approximately here. See detailed geologic maps of this area or make field checks to determine actual outcrop areas.

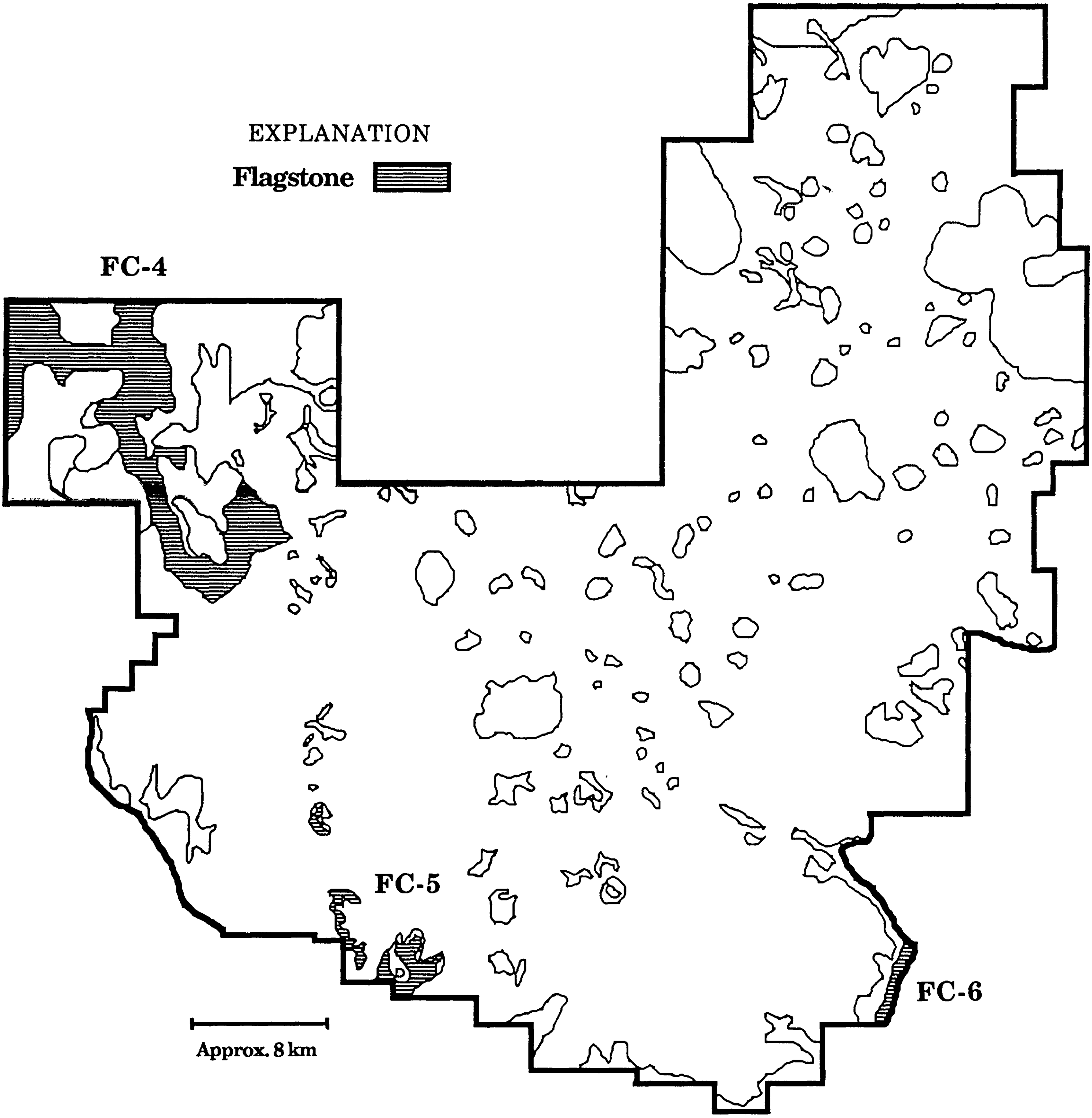

Fig. 12. Permissive tracts for flagstone in the Williams and Chalender Ranger Districts, KNF, Arizona. Delineation should be exclusive to the Coconino Sandstone and Schnebly Hill Formation but may include other units due to small outcrop areas shown at this scale. See detailed geologic maps of this area or make field checks to determine actual outcrop areas. The Ashfork Area (see text) is a part of tract FC-4; the Drake Area is a part of tract FC-5 plus adjacent areas immediately south of KNF.

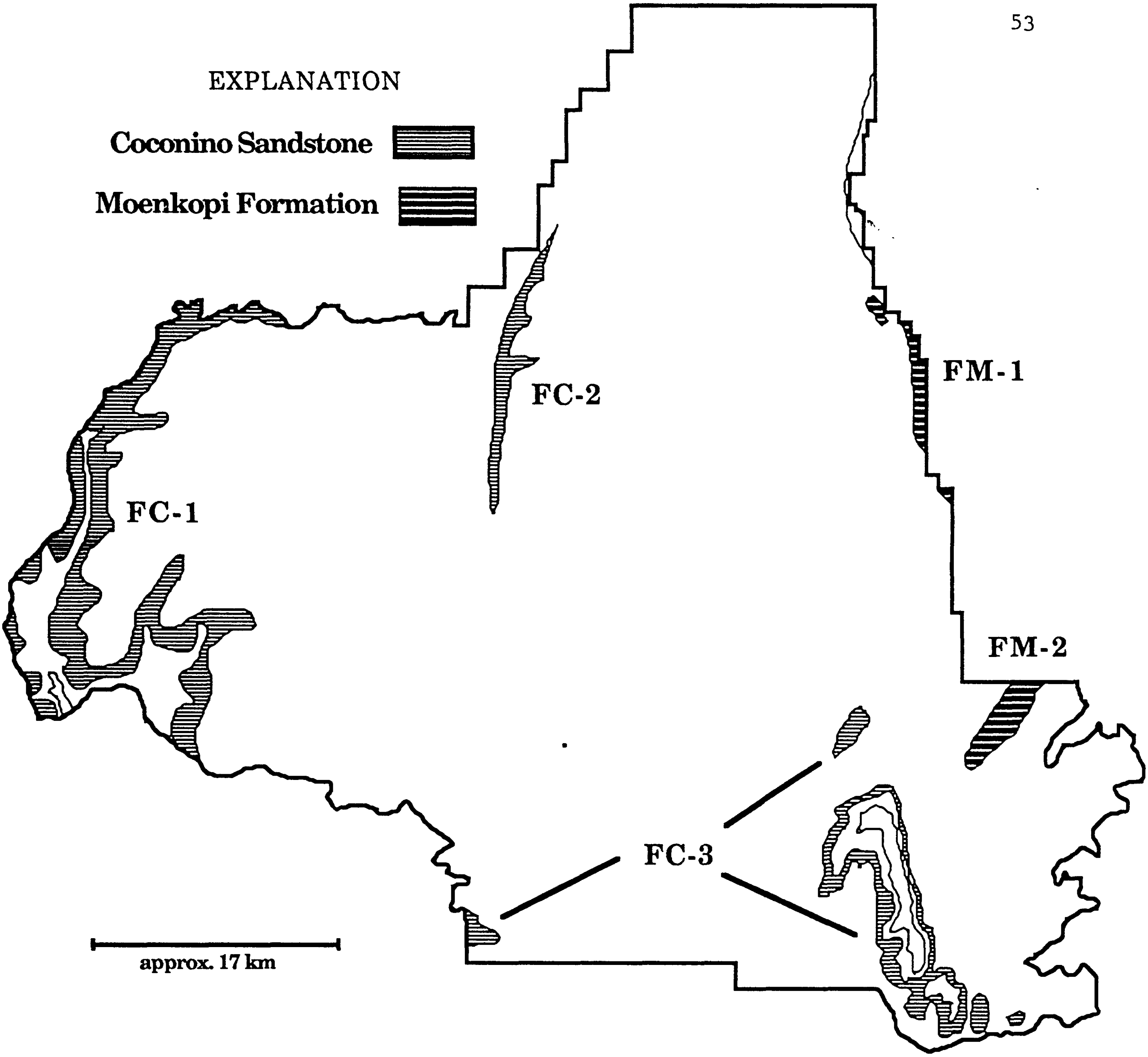

Fig. 13. Permissive tracts for flagstone, and ashlar in the North Kaibab Ranger District, KNF, Arizona. Delineation should be exclusive to the Coconino Sandstone as a source of flagstone (tracts FC-1 to FC-3) and Moenkopi Formation as a source of ashlar (tracts FM-1, FM-2). In the case of the Coconino Sandstone, the Hermit Shale is included due to small outcrop areas at this scale. Other units may be included (or indicated units missed) in error. See detailed geologic maps or make field checks to determine actual outcrop areas.

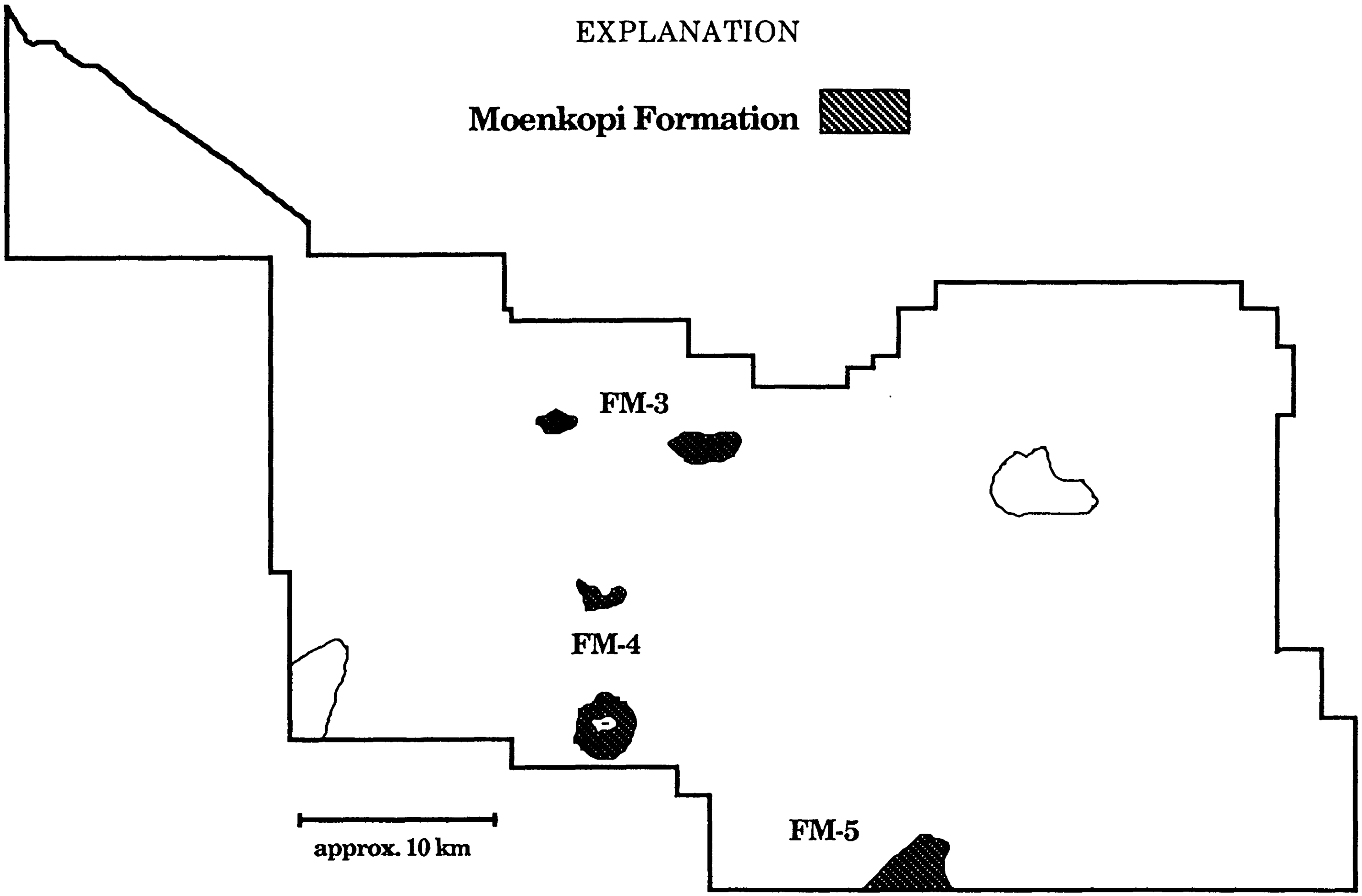

Fig. 14. Permissive tracts for ashlar in the Tusayan Ranger District, KNF, Arizona. Delineation should be exclusive to the Moenkopi Formation (tract FM-3 to FM-5). Other units may be included (or indicated unit missed) in error. See detailed geologic maps or make field checks to determine actual outcrop areas.

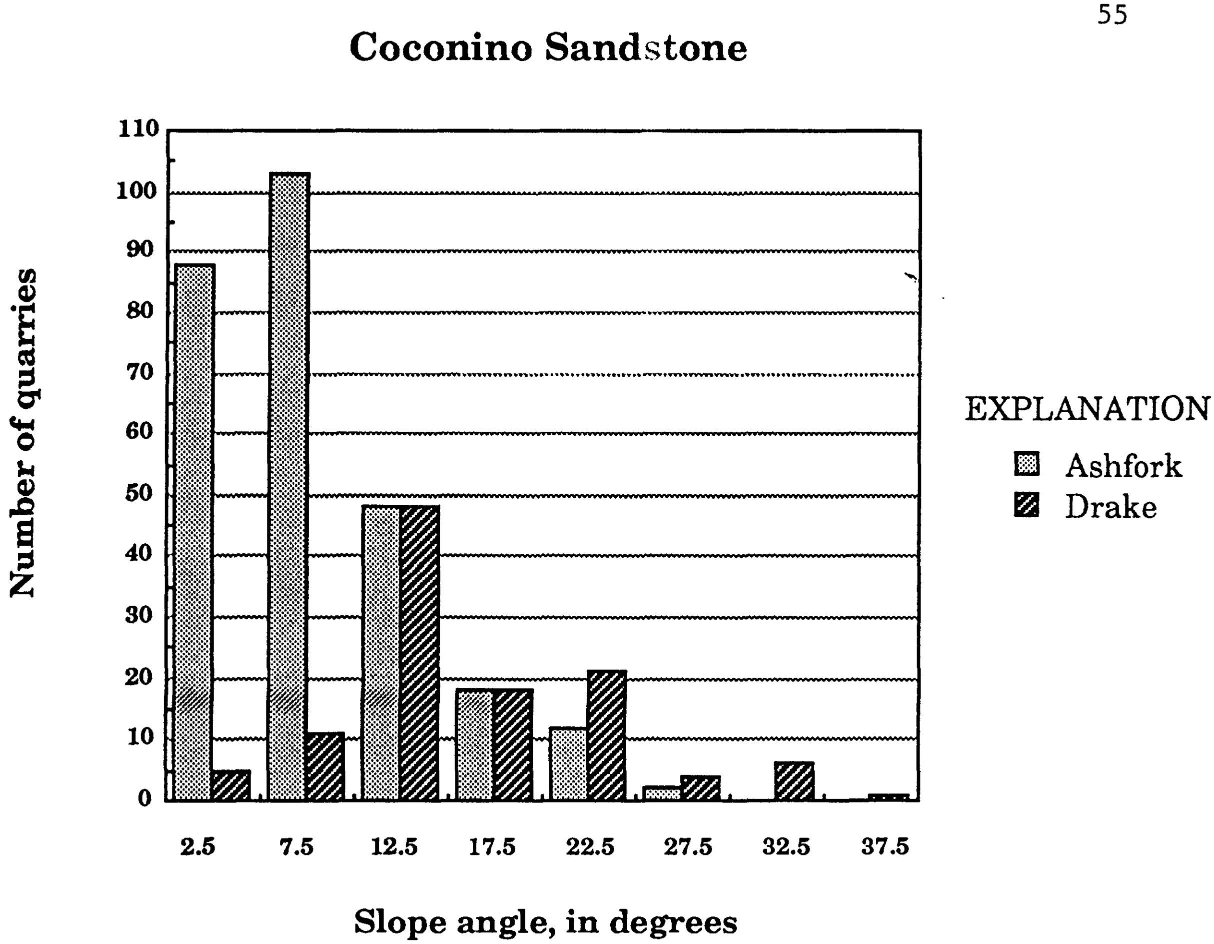

Fig. 15. Topographic slope angle of flagstone quarries found in the Ashfork area and the Drake area.

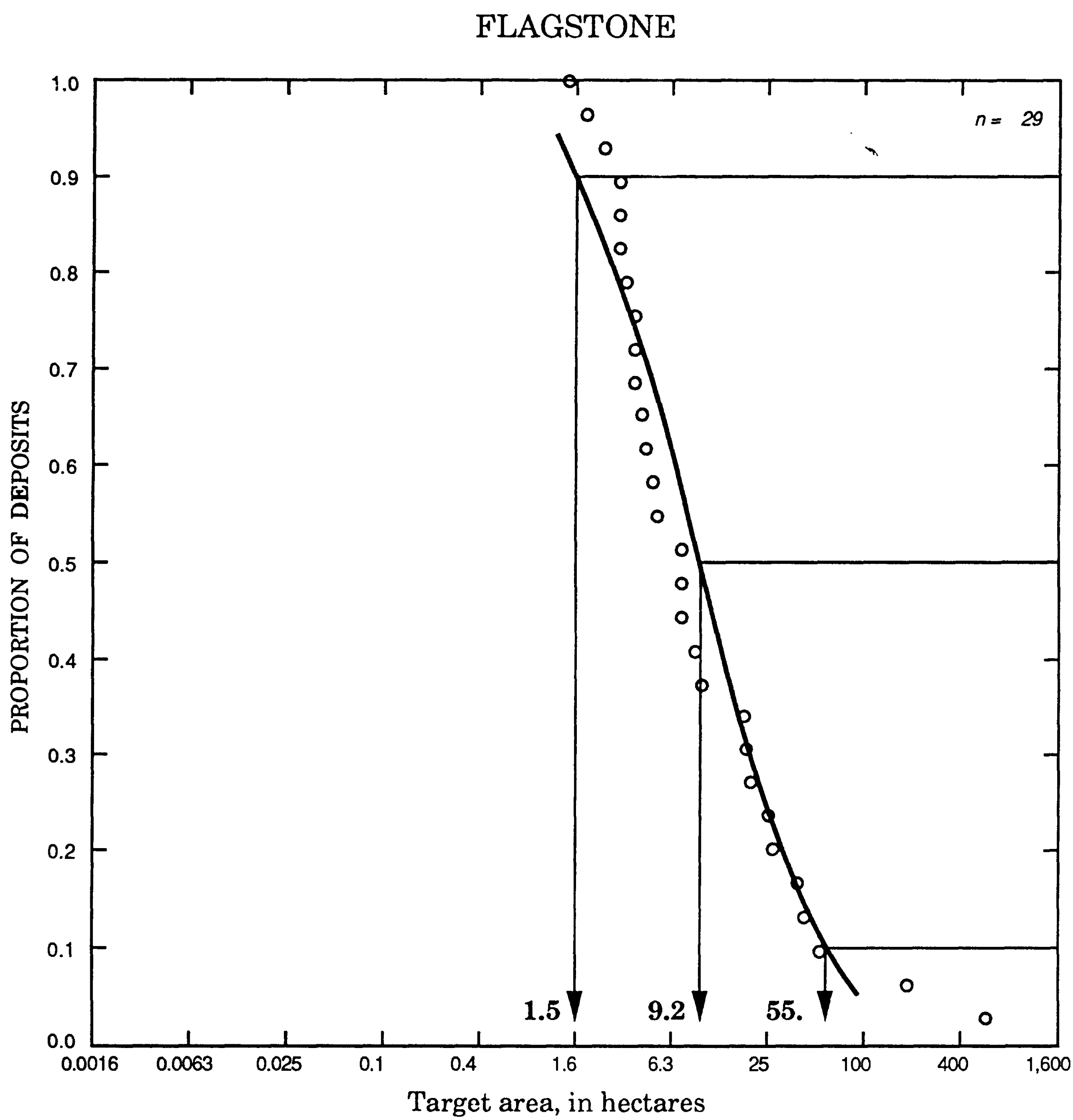

Fig. 16. Model of target areas. Model is for sites with two or more quarries which is 60 percent of the quarry population as shown on 1:24,000 scale topographic maps. Otherwise, the default target area of a single standard quarry is 0.37 ha.

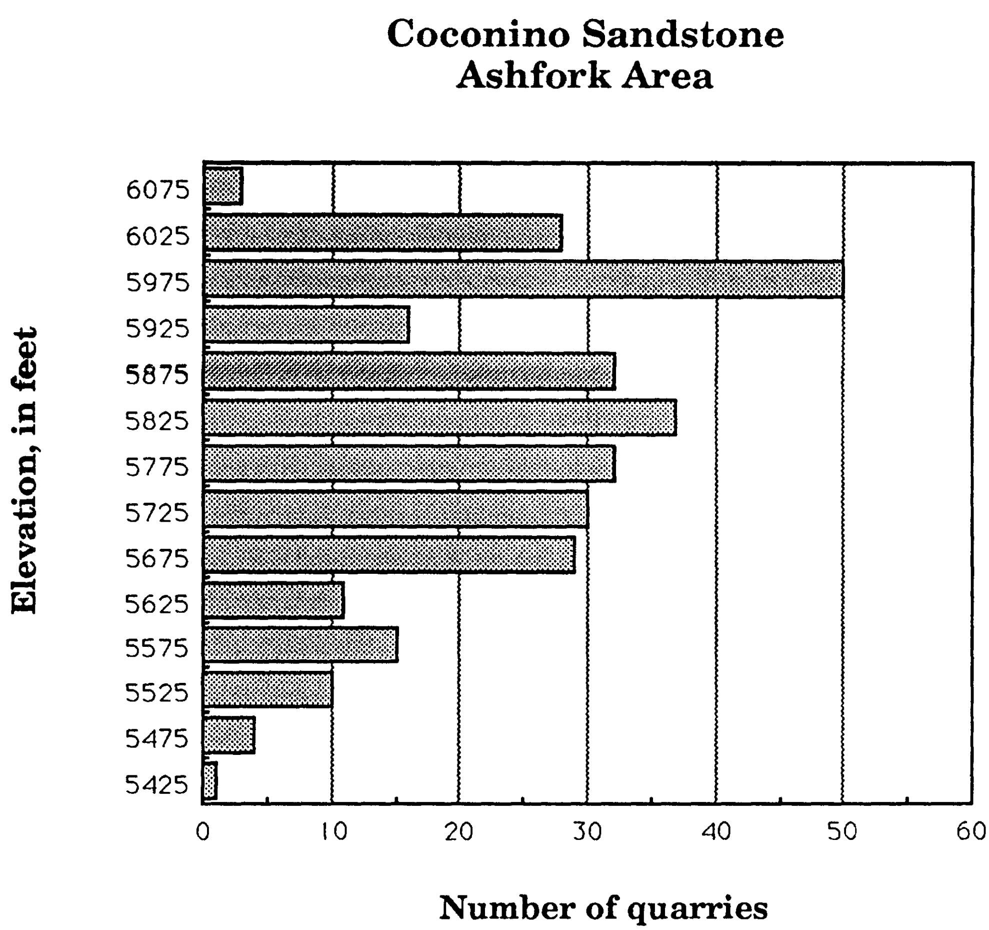

Fig. 17. Distribution of quarries (with elevations) in the Coconino Sandstone, Ashfork Area.

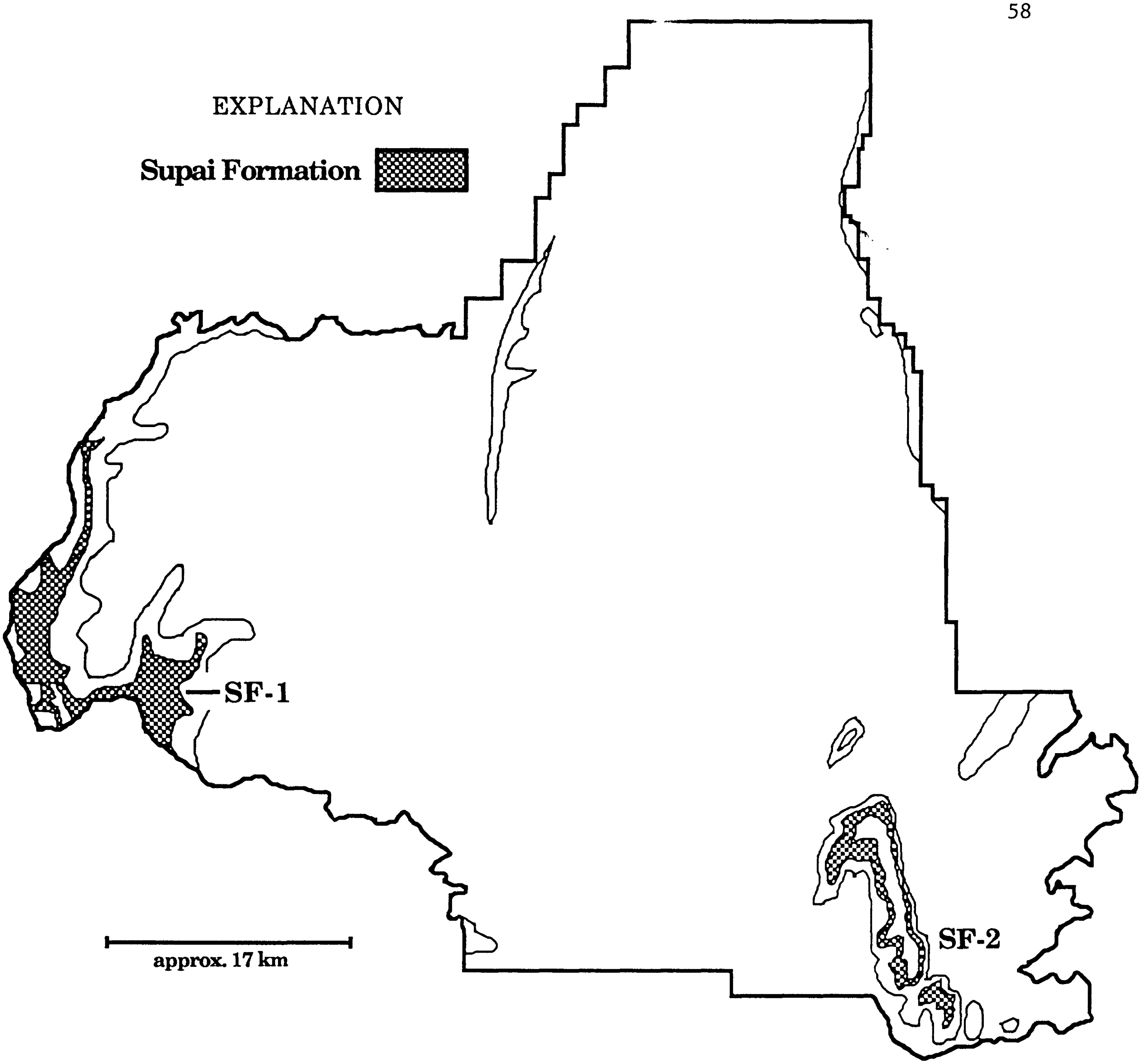

Fig. 18. Permissive tracts for riprap from the Supai Formation in the North Kaibab Ranger District, KNF, Arizona. These generalized delineated tracts should be exclusive to the indicated formation (tract SF-1, SF-2) but may include other units (or missed some part of the indicated formation) in error. See detailed geologic maps of this area or make field checks to determine actual outcrop areas.

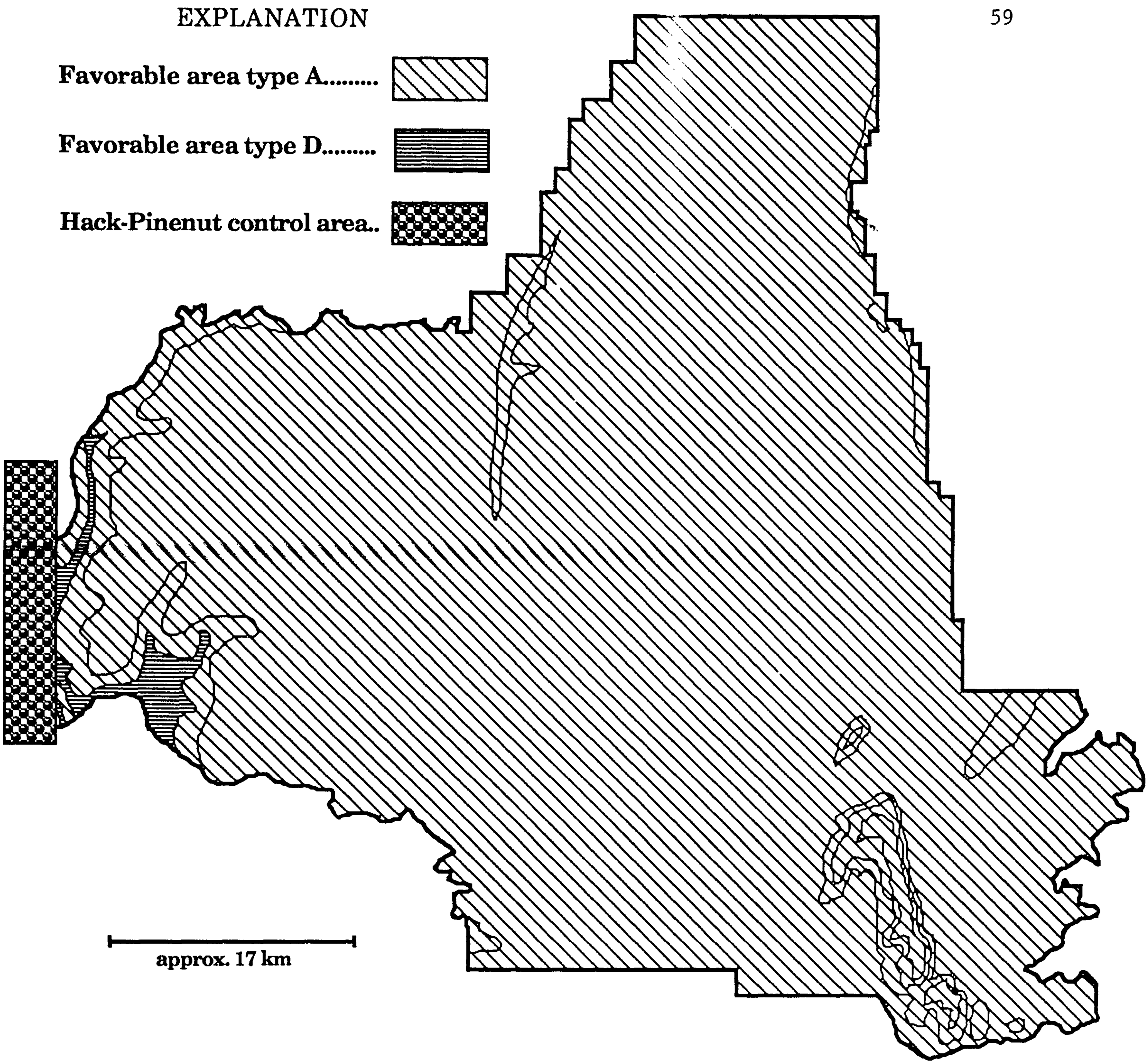

Fig. 19. Favorable area types for undiscovered solution-collapse breccia pipe uranium deposits in the North Kaibab Ranger District, KNF, Arizona. Favorable areas boundaries have been modified slightly to reflect the geology as show here. The Hack - Pinenut Control Area of which only a small part is shown, overlaps the west edge of the forest and is excluded from favorable area designations.

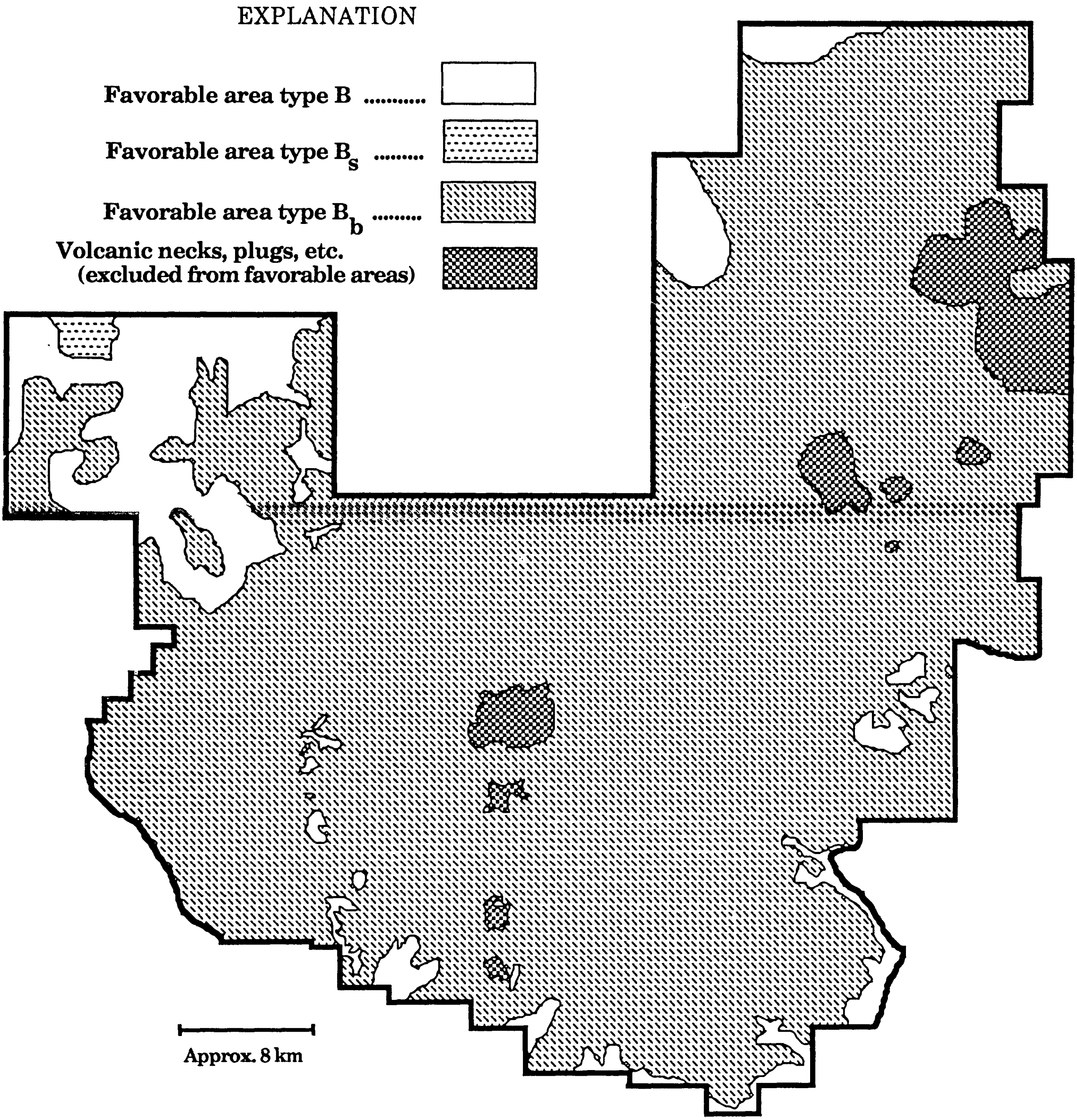

Fig. 21. Favorable area types for undiscovered solution-collapse breccia pipe uranium deposits in the the Williams and Chalender Districts, KNF, Arizona. Favorable area boundaries have been modified slightly to reflect the geology as show here. See text for explanation of subtypes of favorable area type B.