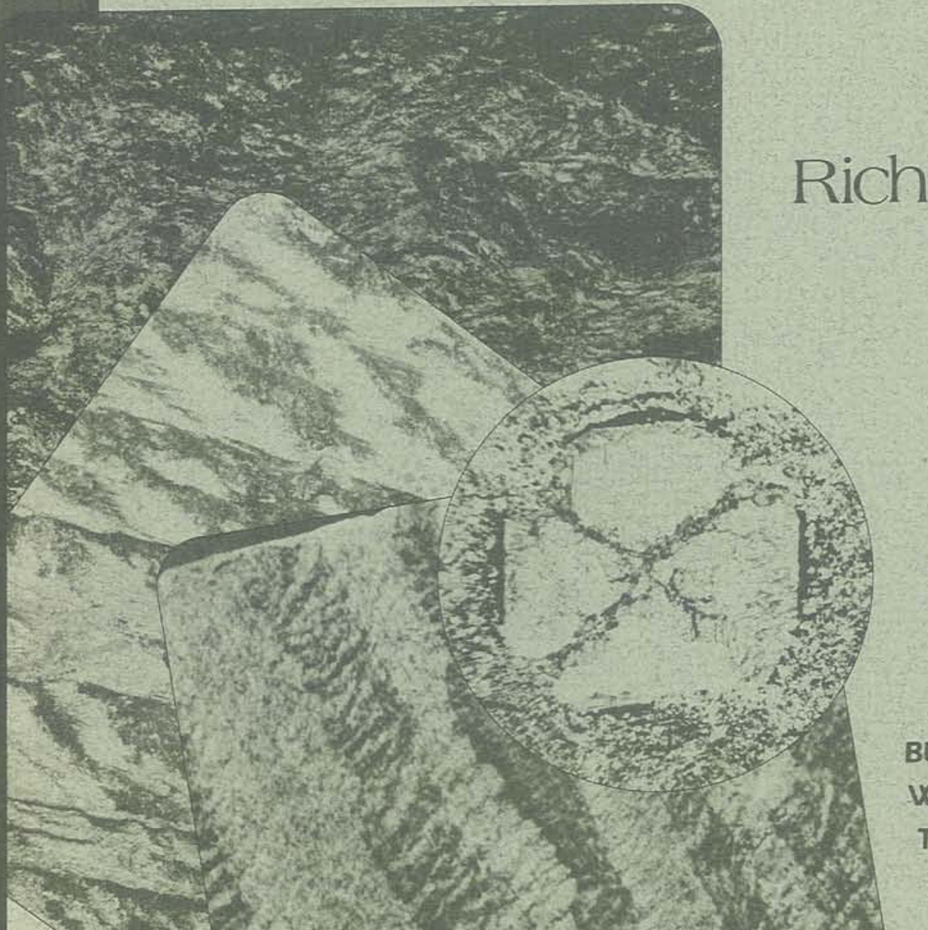
Geological Circular 79-3

Dan Barker

PRECAMBRIAN ROCKS OF THE SOUTHEASTERN LLANO REGION, TEXAS



by

Richard V. McGehee

1979

BUREAU OF ECONOMIC GEOLOGY
W. L. FISHER, DIRECTOR
THE UNIVERSITY OF TEXAS AT AUSTIN
AUSTIN, TEXAS 78712

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PRECAMBRIAN ROCKS OF THE SOUTHEASTERN LLANO REGION, TEXAS

by Richard V. McGehee*

ABSTRACT

Precambrian sedimentary rocks and associated mafic and silicic igneous rocks in Central Texas underwent a single episode of regional metamorphism about 1,050 million years (m.y.) ago. In the final stages of metamorphism great masses of granite and innumerable small pegmatite bodies intruded the older sedimentary and igneous rocks. The Llano Supergroup, stratiform metamorphic rock more than 28,000 ft (8,400 m) thick, includes two groups: the Valley Spring Gneiss, consisting mostly of quartz-feldspar gneiss; and the overlying Packsaddle Schist, composed of marble, graphite schist, amphibole schist, mica schist, and leptite. Four new formations, Honey, Sandy, Rough Ridge, and Click (from oldest to youngest), are proposed as subdivisions of the Packsaddle Schist. Metamorphosed intrusive igneous rocks include Coal Creek Serpentine, Big Branch Gneiss, Red Mountain Gneiss, and many small bodies of metagabbro and metagranite.

Grade of most of the metamorphic rocks is almandine-amphibolite facies. Andalusite, sillimanite, and cordierite are widespread but not abundant in the pelitic rocks. Diopside and tremolite are common in marble and calc-silicate hornfels. Contact metamorphism near granite bodies probably approached the pyroxene-hornfels facies.

Major structural elements of the area are the broad regional southeast-plunging Babyhead - Indian Flat anticline and three northwest-trending thrust faults, which may have been caused by forceful batholithic intrusion. Foliation is generally parallel to original bedding and lineation is generally parallel to major fold axes. Some of the rocks also possess an axial plane foliation, and others have additional lineations (mostly at high angles to fold axes).

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INTRODUCTION

The apex of the Llano Uplift, also known as the Llano region and as the Central Mineral Region, contains the largest area of exposed Precambrian rocks in Texas. The only other exposures are in West Texas in the Van Horn area, in the Pump Station Hills and the Hueco Mountains, and in the Franklin Mountains near El Paso. The Llano Uplift is a large structural dome with Precambrian crystalline rocks surrounded by Paleozoic and Cretaceous sedimentary rocks. The structurally highest part of the uplift is a topographic basin, bounded by highlands consisting of relatively resistant Paleozoic and Mesozoic rocks. Erosional remnants and downthrown fault blocks of Paleozoic rocks form isolated hills in the basin.

The following list gives all Precambrian units of the Llano region in approximate order of increasing age.

Quartz-feldspar porphyry (Llanite) dikes (Iddings, 1904)
Sixmile Granite (Stenzel, 1932)
Oatman Creek Granite (Stenzel, 1932)
*Pegmatite, aplite and granite; quartz veins (not named)
*Melarhyolite dike (not named)
*Town Mountain Granite (Stenzel, 1932)
*Mafic dikes (not named)
*Talc, soapstone and tremolite rock (not named)
*Coal Creek Serpentine (Barnes, 1940)
*Hornblende metadiorite (not named)
*Orthoamphibolite and hornblende rock (not named)
*Red Mountain Gneiss (Romberg and Barnes, 1949; Barnes and others, 1950)
*Big Branch Gneiss (Barnes, 1940)
*Llano Supergroup (Series) (Walcott, 1884)
    *Packsaddle Schist (Comstock, 1890)
        *Click Formation (new name)
        *Rough Ridge Formation (new name)
        *Sandy Formation (new name)
        *Honey Formation (new name)
    Lost Creek Gneiss (Ragland, 1960)
    *Valley Spring Gneiss (Comstock, 1890)

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*Rocks found in the Southeastern Llano region.

STRATIGRAPHY

Llano Supergroup

In this report, all of the metasedimentary rocks of the southeastern part of the Llano region are placed in the Llano Supergroup, named for typical exposures in Llano County. Although the rocks are now known to be Precambrian, this usage conforms to the first usage of the term "Llano" (Walcott, 1884, p. 431-432), and to subsequent U.S. Geological Survey usage (Paige, 1912, p. 3). The designation "series" is replaced by "supergroup" according to modern stratigraphic nomenclature. The Llano Supergroup contains the Valley Spring Gneiss and the overlying Packsaddle Schist. Rocks of the Llano Supergroup are older than the granite (Town Mountain Granite) that intruded them, which is about 1,050 million years (m.y.) old. Zartman (1964, p. 376) analyzed Valley Spring and Packsaddle samples and found the age of metamorphism to be indistinguishable from the age of Town Mountain Granite intrusion.

Valley Spring Gneiss

Valley Spring Gneiss, confined to the Cap Mountain quadrangle, forms the core of the Babyhead anticline and occupies the northwest corner of the area shown in plate 1. It is dominantly pink quartz-feldspar gneiss, mineralogically and chemically closer to granite than to rocks of the Packsaddle Schist. No stratigraphic sections of the Valley Spring were measured, but in its outcrop area northwest of Packsaddle Mountain, three divisions of the formation were mapped:

Unit		Approximate thickness	
		ft	m
C -	Pink quartz-feldspar gneiss, well foliated, and pink leptite; gray gneiss with pink feldspar augen near the top of the unit; conformably underlies the Packsaddle Schist	130	40
B -	Gray quartz-feldspar-biotite gneiss	250	75
A -	Pink quartz-feldspar gneiss, poorly to fairly well foliated; contains much pegmatitic material, especially in lower part of the unit; biotite schist and amphibole schist are present in very small amounts; base not reached in area of study	8,100	2,440
	Total	8,480	2,555

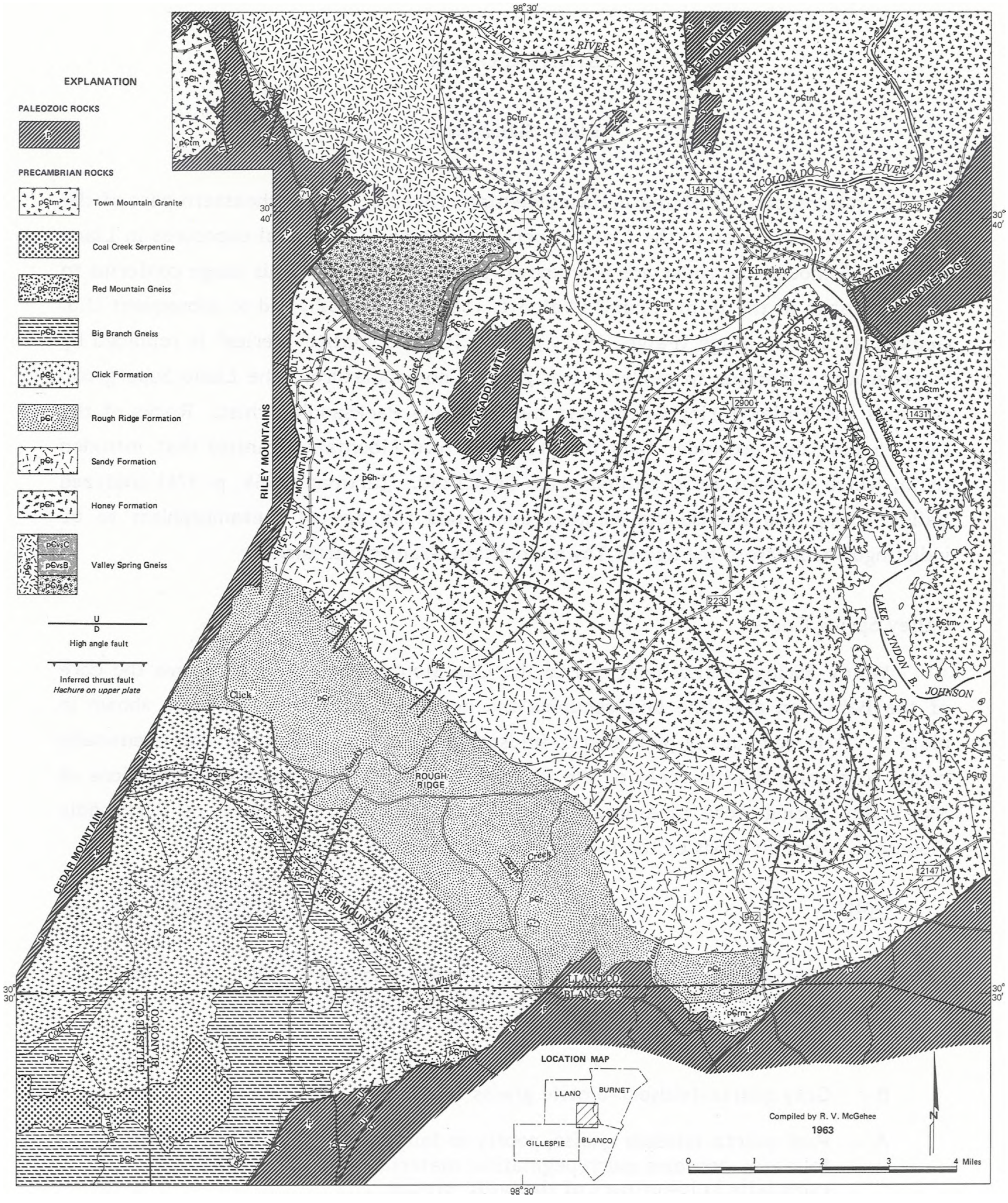
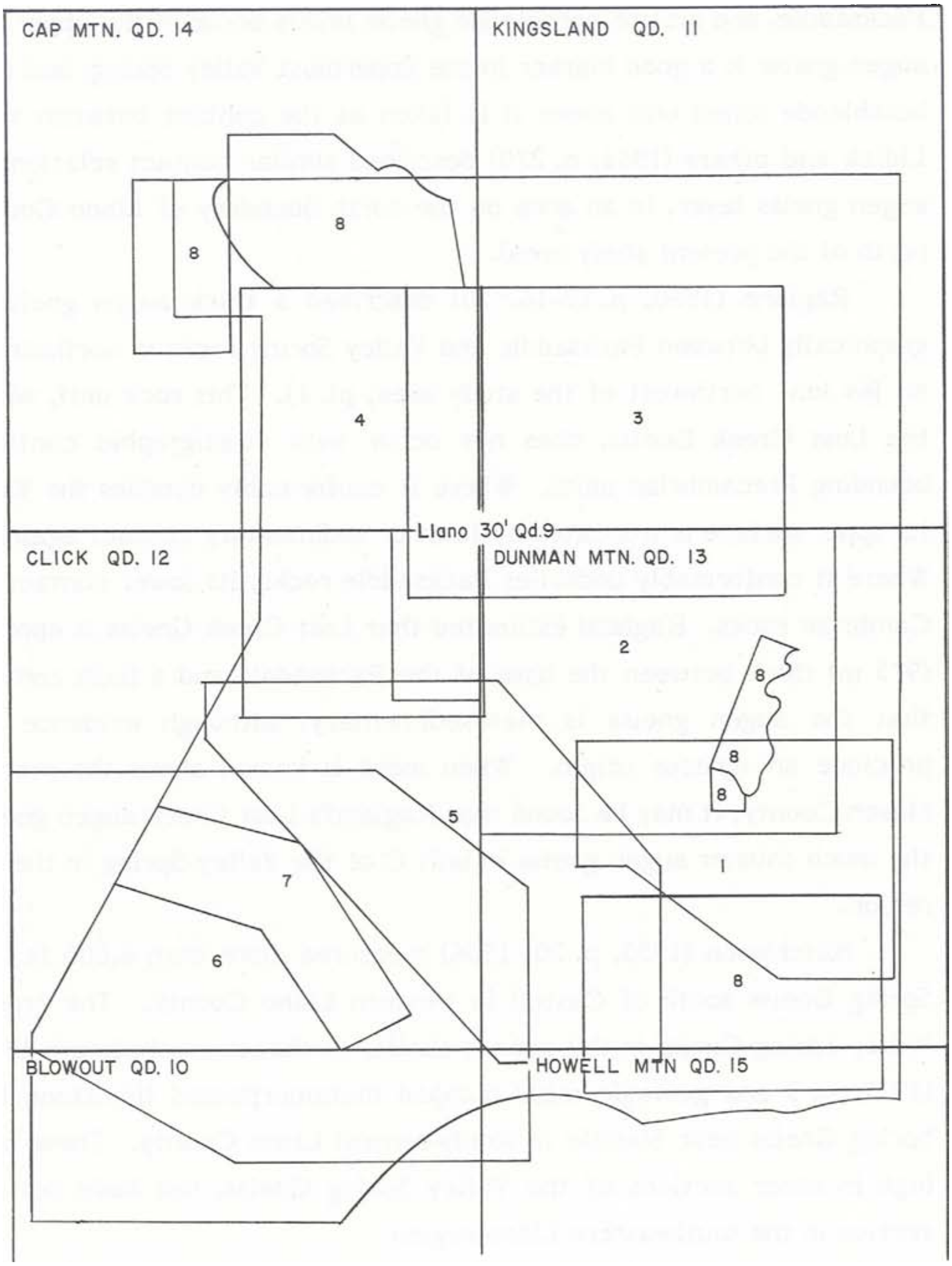


Plate 1. Geologic map of southeastern Llano region, Llano, Burnet, Blanco, and Gillespie Counties, Texas. (Index of original geologic mapping of Precambrian rocks is on facing page)

1. McCandless (1957)
2. Sims (1957)
3. Doyle (1957)
4. Blount (1962) and McGehee (1963)
5. Anderson (1960)
6. Burnitt (1961)
7. Clabaugh and Boyer (1961)
8. McGehee (1963)
9. Paige (1912)
10. Barnes (1952)
11. Barnes (1976)
12. Barnes (1978)
13. Barnes (1978)
14. Barnes (1978)
15. Barnes (1978)



The Valley Spring - Packsaddle contact is gradational (over a thickness of more than 100 ft [30 m] in places); layers of pink quartz-feldspar gneiss occur in the basal Packsaddle, and biotite-hornblende gneiss layers occur in the upper Valley Spring. The augen gneiss is a good marker in the uppermost Valley Spring, and the base of the first hornblende schist unit above it is taken as the contact between the two formations. Lidiak and others (1961, p. 270) described similar contact relationships, including the augen gneiss layer, in an area on the north boundary of Llano County (20 mi [32 km] north of the present study area).

Ragland (1960, p. 13-16, 20) described a thick augen gneiss sequence, stratigraphically between Packsaddle and Valley Spring rocks in northern Mason County (40 mi [64 km] northwest of the study area, pl. 1). This rock unit, which Ragland called the Lost Creek Gneiss, does not occur with stratigraphic continuity between the bounding Precambrian units. Where it conformably overlies the Valley Spring Gneiss, its upper surface is truncated by fault or sedimentary contact against Cambrian rocks. Where it conformably underlies Packsaddle rocks, its lower contact is likewise against Cambrian rocks. Ragland estimated that Lost Creek Gneiss is approximately 3,200 ft (975 m) thick between the base of the Packsaddle and a fault contact. He concluded that the augen gneiss is metasedimentary, although evidence does not entirely preclude an igneous origin. When more is known about the metamorphic rocks of Mason County, it may be found that Ragland's Lost Creek augen gneiss correlates with the much thinner augen gneiss in unit C of the Valley Spring in the southeastern Llano region.

Hutchinson (1953, p. 20; 1956) measured more than 6,000 ft (1,820 m) of Valley Spring Gneiss south of Castell in western Llano County. The gross lithology of the Valley Spring Gneiss in this area is similar to that in southeastern Llano County. Paige (1912, p. 3 and geologic map) mapped metamorphosed limestone beds in the Valley Spring Gneiss near Sixmile in south-central Llano County. These beds are apparently high in other sections of the Valley Spring Gneiss, but have not been found in the section in the southeastern Llano region.

Stenzel (1935, p. 74) interpreted the Valley Spring as meta-igneous rock that intruded into the Packsaddle during regional metamorphism. The great thickness of rock of granitic composition and almost unvarying appearance does suggest an igneous origin. However, sedimentary origin of the Valley Spring Gneiss seems to best explain the following features:

1. Layers of schist and calc-silicate rock (originally shale and limestone) lie conformably within the Valley Spring.
2. The Valley Spring - Packsaddle contact is conformable.
3. Gneiss layers alternating with hornblende schist in the basal Packsaddle suggest a stratiform sequence composed originally of sandstone and shale.
4. No contact metamorphic effects have been reported at Valley Spring - Packsaddle contacts (such effects are common at Town Mountain - Packsaddle contacts).
5. Foliation in the Valley Spring is fairly well developed, and layering on a scale larger than foliation is present in the upper part of the gneiss (such as the gray gneiss unit B, which is mappable laterally for at least 3 mi [4.8 km]; and the augen gneiss layer at the top of the Valley Spring, which occurs in two localities 20 mi [32 km] apart and possibly also in Mason County).
6. No relic features of an intrusive contact (such as xenoliths of Packsaddle rocks near the Valley Spring - Packsaddle contact, irregularities along the contact or fingers of gneiss extending into the Packsaddle, chill zones in the gneiss at the contact, or mylonitization of the Packsaddle) have been reported.
7. Within the Valley Spring lie discordant bodies of poorly foliated granitic rock that are intrusive into the gneiss.
8. Grain size of the gneiss is much finer and more uniform than that of most igneous rocks that occur in thick intrusive bodies.

A third interpretation of the Valley Spring is that it was mostly rhyolitic volcanic rock (lava, tuff). The features pointing toward sedimentary origin are also somewhat compatible with volcanic origin. In this case the discordant bodies of granitic rock within the gneiss could have been volcanic necks. On the basis of his chemical study of 10 Valley Spring samples, Billings (1962, p. 349) could not distinguish between sedimentary and igneous origin.

Metamorphosed intrusive igneous rocks within the Valley Spring Gneiss include (1) biotite schist, vermiculite, soapstone, and serpentine from highly mafic intrusives; (2) metagranite; (3) orthoamphibolite; and (4) metadolerite. Of these, only the metagranite occurs in the southeastern Llano region.

Packsaddle Schist

Rocks of the Packsaddle Schist make up most of the area of metamorphic rocks shown in plate 1. The most continuous and best exposed Packsaddle sequence in the Llano region is found in this area.

No section of Packsaddle had previously been measured and designated as a type section. A composite section totaling more than 20,000 ft (6,000 m) was measured during the spring of 1962, and it is proposed here as the type section of the Packsaddle Schist. The section lies along Honey, Cottonwood, and Sandy Creeks, and on a portion of the J. L. Pearson ranch. Formations of the Packsaddle proposed here take their names from geographic features along or near the measured type section. Definition of these formations is based on the measured section and mappability of the units over the area of study.

Honey Formation (new name)

The lowest division of the Packsaddle is the most variable in lithology. Its base is well exposed in Honey Creek, northwest of Packsaddle Mountain (pl. 1 and Cap Mountain quadrangle). The upper part is well exposed along Sandy Creek from State Highway 71 bridge to the creek's mouth (pl. 1 and Dunman Mountain quadrangle). Composite thickness of the Honey Formation along these streams is 8,290 ft (2,530 m). The lower boundary of the formation coincides with the contact between the Valley Spring Gneiss and Packsaddle Group, that is, the base of the first dark-gray hornblende schist - phyllite unit which lies above the augen gneiss layer of the Valley Spring. The upper boundary is the top of the stratigraphically highest marble bed.

Defined by these boundaries, the Honey Formation contains all of the marble, calc-silicate rock, and graphite schist of the Packsaddle. These three rock types characterize the formation, but it also further contains other various rocks, including leptite, quartz feldspar gneiss, biotite schist, hornblende schist, and a thick unit of muscovite schist. From the base upward the gross sequence in the vicinity of the measured section is (1) alternating hornblende schist and leptite, including a unit of diopside rock and marble; (2) alternating marble and graphite schist; (3) biotite schist and amphibole schist; (4) graphite schist; (5) muscovite schist, including two prominent marble units; (6) graphite schist and hornblende-graphite schist, including a trace of marble; and (7) amphibole schist with a trace of marble.

One of the most striking departures from the type section is in the far northwest part of the map area (pl. 1 and Cap Mountain quadrangle), where the dominant rock type is gray leptite. Marble and graphite schist are present but much less abundant than in the type section, and amphibole schist is absent entirely. The rocks in this area occupy the position of the basal approximately 3,450 ft (1,050 m) of the formation.

Another major sedimentary facies change is indicated by the disappearance to the southeast of the thick muscovite schist unit of the measured section, and its replacement by amphibole and graphite schists. This part of the section is partly cut out in this area by a thrust fault.

Three rock types present only on the east limb of the Babyhead - Indian Flat anticline are (1) chiastolite-graphite schist, (2) highly lineated pyrite-bearing hornblende-quartz schist, and (3) units of marble thinly interbedded with calc-silicate rock, leptite, and hornblende-quartz schist.

In the Little Llano River area, about 20 mi (32 km) north of the present area of study, Lidiak and others (1961, p. 271) described 3,300 ft (1,000 m) of Packsaddle rock overlying the Valley Spring Gneiss. The rock is dominantly hornblende schist, with lesser amounts of marble, quartz-feldspar rock, and quartz-mica schist. This section is similar to the lower part of the Honey Formation in its type section but contains more hornblende schist.

Sandy Formation (new name)

The Sandy Formation overlies the Honey Formation. The type section (pl. 1) is along Sandy Creek, from near State Highway 71 bridge (Dunman Mountain quadrangle) to near the mouth of Cottonwood Creek (Click quadrangle). A representative section, generally better exposed but covered at the base, is in a dry branch of Cottonwood Creek. In the type section the lower boundary of the formation is placed where the highest marble bed in the Honey Formation contacts an overlying leptite unit. The formation consists of alternating units of quartz-feldspar rock and hornblende schist. Where the marble bed at the top of the Honey Formation is covered or absent, the contact between the two formations is determined to be at the base of the lowest thick quartz-feldspar rock unit above a mixed unit of fine-grained reddish weathering hornblende schist, gray leptite, and thin marble beds. The top of the Sandy Formation is located at the top of the highest hornblende schist unit.

In the type section the formation is 2,290 ft (700 m) thick; in the representative section it is 1,915 ft (585 m) thick. In both sections the formation contains, from bottom to top, (1) leptite, (2) hornblende schist, (3) leptite, and (4) hornblende (and tremolite) schist.

In the Mesquite Hill area southeast of the type section, the upper part of the Sandy Formation is a very thick unit of light-pink leptite, much of which is difficult to distinguish from Red Mountain Gneiss. The formation in this area consists of only three general parts: lower and upper leptite units and a middle hornblende schist unit. Across the Hardin Hills thrust fault to the east, about 5,500 ft (1,650 m) of dominantly leptite and quartz-feldspar-mica schist exists between the top of the Honey Formation and the Precambrian-Paleozoic border fault.

Rough Ridge Formation (new name)

The Rough Ridge Formation overlies the Sandy Formation. Its type locality is along Sandy Creek (Click quadrangle), upstream and downstream from Rough Ridge. This formation contains a great thickness of gray quartz-feldspar rock of extremely uniform lithology. Some white muscovite schist occurs in the lower half of the formation, and a gray biotite gneiss unit with large cordierite porphyroblasts near its base is in the upper half of the formation. The base of the formation is the contact between the uppermost hornblende schist (hornblende-diopside rock in the type section) of the underlying Sandy Formation and the overlying massive gray leptite and quartz-feldspar schist. The top of the formation is the base of a greenish-gray actinolite schist unit.

Excluding meta-igneous rock, the formation is 5,370 ft (1,640 m) thick in the type section. The tough gray Rough Ridge leptite appears distinctly different from the light-gray, light-pink, and light-brown leptite of the underlying Sandy Formation. This distinction is important in inferring the existence of the Hardin Hills thrust fault in the Mesquite Hill area.

Click Formation (new name)

The Click Formation overlies the Rough Ridge Formation and is the uppermost subdivision of the Packsaddle in the southeastern Llano region. It is a poorly defined unit because it contains large amounts of meta-igneous rock. The top of the formation is cut off by Big Branch Gneiss (an orthogneiss). The type section for the basal part of the formation is on the J. L. Pearson ranch, about 1 mi (1.6 km) southwest of Click (pl. 1 and Click quadrangle). The name "Click" was used by Comstock (1890, p. 274) as a series term, but because his stratigraphic terminology is not valid, the name is redefined in this study. The base of the member is a greenish-gray actinolite schist unit overlying the quartz-feldspar rock of the Rough Ridge Formation. Most of the rock above the actinolite schist in the type section is light brown to pink leptite and quartz-feldspar schist. Excluding meta-igneous rock (Red Mountain Gneiss), the lower part of the formation is 3,410 ft (1,040 m) thick. Rock of the Click Formation stratigraphically higher than that in the measured section is mostly hornblende schist. Its thickness, estimated from outcrop width and average dip, is about 3,800 ft (1,155 m).

Interpretation of the Llano Supergroup

The rock that was metamorphosed to become the Valley Spring Gneiss and Packsaddle Schist was originally deposited in a sedimentary basin. No direct evidence has been found that indicates the shape and size of this basin, but some inferences can be made about the premetamorphic rocks.

The rock that was to become Valley Spring Gneiss, the oldest rock recorded in the Llano area, was either a thick, uniform sequence of arkose or an accumulation of silicic lavas and pyroclastic rocks. The protoliths of the Packsaddle, which were deposited on the Valley Spring sequence, were sedimentary rocks chemically unlike the older unit. The basal Packsaddle is characterized by abundant hornblende schist - phyllite, which was probably shale originally. The transition from sandstone, now Valley Spring Gneiss, to an alternating sandstone and shale sequence, might have resulted from a change in source rock or a change in the depositional environment.

Chemical evidence points toward an igneous origin for at least some of the basal Packsaddle hornblende schist (Billings, 1962, p. 343-347). Some of this rock could have originally been basaltic lava flows or pyroclastic sediment rather than shale.

The lower Honey marble and calc-silicate layers contain little graphite and may originally have been mostly inorganic chemical deposits. Those higher in the section are nearly all associated with graphite schist, and many contain small amounts of graphite. This increase in carbon suggests an increase in organic material, and probably means that the upper marble and calc-silicate layers had an organic origin--they were possibly built by calcareous algae. The Sandy Formation was probably a sandstone and shale sequence. The Rough Ridge Formation was mostly impure sandstone; the Click Formation was mostly sandstone in the lower part and shale in the upper part.

Metamorphosed Igneous Rocks

Big Branch Gneiss crops out in the southwest corner of the area (pl. 1, Blowout and Click quadrangles). It is metamorphosed quartz diorite with abundant inclusions of Packsaddle rock. The Big Branch is apparently younger than most of the ortho-amphibolite (Click quadrangle) where the two are interlayered (Burnitt, 1961, p. 81). It has been feldspathized by the Red Mountain in places near their contact and is therefore older than the Red Mountain Gneiss (Clabaugh and Boyer, 1961, p. 11, 15).

Coal Creek Serpentine crops out in the Blowout quadrangle to the southwest and extends to the Willow City quadrangle west of the area in plate 1. It is a metamorphosed ultramafic igneous rock that intruded the Packsaddle and is possibly younger than the Big Branch intrusives (Burnitt, 1961, p. 75).

Red Mountain Gneiss is metagranite that was emplaced in the southwestern part of the area mostly as sills. The Red Mountain Gneiss appears to be the youngest metamorphic rock in the area, but its relationships to the Coal Creek Serpentine and to certain mafic dikes are unknown. The metagranite bodies within the Valley Spring to the north (Cap Mountain quadrangle) may be Red Mountain Gneiss.

Igneous Rocks--Town Mountain Granite

The Town Mountain Granite (pl. 1) is coarse grained, mostly porphyritic, pink, and lies mainly along the eastern edge of the map area in the Kingsland, Dunman Mountain, and Cap Mountain quadrangles. An isolated mass crops out in the west-central part of the Cap Mountain quadrangle. A large granite mass borders Cedar Mountain on the west and may extend beneath the Paleozoic cover almost to the eastern side of Cedar Mountain. The Town Mountain Granite is the oldest of Stenzel's three named granites in the region (1932, p. 144) and is the youngest named Precambrian unit within the map area. Samples of Town Mountain Granite analyzed by Tilton and others (1957, p. 364) were determined to be an average of 890 to 1100 m.y. old by different dating methods. More recent work by Zartman (1964, p. 397) produced dates that average 1020 m.y. (Rb-Sr) and 1045 m.y. (K-Ar).

Evidence of the intrusive nature of Town Mountain Granite includes the following: (1) steep dip, contorted foliation, and brecciation of country rock near granite contacts; (2) sharp contacts with country rock and xenoliths near borders of granite bodies; (3) metasomatic and contact metamorphic minerals (tourmaline, wollastonite, idocrase, andalusite, sillimanite) in country rock near contacts with granite and associated dike rocks; (4) introduction of large amounts of potassium, converting andalusite, sillimanite, and cordierite to muscovite and sericite; (5) flow structure expressed by oriented microcline and perthite phenocrysts, schlieren, and xenoliths in the granite (Hutchinson, 1956, p. 769-777; Keppel, 1940, p. 983-984); (6) mineral paragenesis; and (7) textural zoning conformable to the model of a cooling magma (Keppel, 1940, p. 981-983).

STRUCTURE

The major regional Precambrian structural features in metamorphic rocks of the Llano region are the broad southeast-plunging Babyhead - Indian Flat anticline and the Click syncline. The large Town Mountain Granite mass in the Kingsland - Marble Falls area occupies the original position of a syncline east of the Babyhead anticline.

Stenzel (1935, p. 74-75) believed that the Packsaddle was deformed in isoclinal folds. He interpreted a series of 17 marble beds east of Oxford (about 10 mi [16 km] west of the area in pl. 1) as a few beds repeated in isoclinal folds.

In the southeastern Llano region the regional folds were probably not preceded by any significant amount of large scale isoclinal folding. Crestal portions of isoclinal folds have not been described, and the stratigraphic sequence does not include the inversions that would be caused by such folds.

Major Folds and Faults

In the northwestern part of the plate 1 area (Cap Mountain quadrangle) the Babyhead anticline is a simple asymmetric anticline with a narrow, steeply dipping eastern limb abutting Town Mountain Granite of the Kingsland - Granite Mountain pluton, and a broad, gently dipping western limb which is overlapped at Riley Mountain and Cap Mountain by Cambrian sedimentary rocks. The anticline plunges 15 to 25 degrees to the southeast. Farther south, near the Valley Spring - Packsaddle contact north of Packsaddle Mountain, the structure is more complex. The crest is made up of two anticlines with axes about 8,500 ft (2,550 m) apart, separated by a shallow syncline. This double-crested fold continues to the southeast and is particularly conspicuous in the prominent marble beds about 2 mi (3.2 km) southeast of Packsaddle Mountain. In the Riley Mountain - Cedar Mountain vicinity where Paleozoic rocks are downfaulted, the western limb of the anticline passes beneath the Paleozoic rocks.

North of Packsaddle Mountain the rocks on the western flank of the broad anticline dip consistently 30 to 40 degrees to the west, and on the eastern flank, 75 degrees to the east; in one or two places strata are overturned. The steeper dips on the eastern flank were caused by forceful intrusion of the Kingsland pluton. It is likely that the pre-Town Mountain structure in this vicinity was much more symmetrical. Wrinkling of the broad anticlinal nose into its double-crested form may have resulted from compression accompanying granite intrusion. This wrinkling is more strongly developed to the southeast on the Dunman Mountain quadrangle, where a tightly folded anticline-syncline-anticline structure exists.

The Llano syncline, a broad regional fold about 10 mi (16 km) west of the Babyhead - Indian Flat anticline, occurs in the southwest part of the map area, north of the meta-igneous complex, as a rather subtle feature here called the Click syncline. North of Sandy Creek it plunges 25 to 35 degrees nearly due south. Southward in a complex of orthogneiss and serpentine, the synclinal pattern can be seen in the trend of sill-like amphibolite bodies. Its plunge increases there to as much as 60 degrees. Near the Coal Creek Serpentine mass, steep (60 to 80 degrees) opposing dips in large Packsaddle inclusions within Big Branch Gneiss suggest a tight, approximately symmetrical syncline.

Only a few faults known to be Precambrian have been mapped in the southeastern Llano region, mostly in the Dunman Mountain quadrangle. This is probably because faulting during the orogeny that accompanied regional metamorphism was largely healed or obscured by the metamorphism. It is difficult to distinguish younger (post-metamorphism) Precambrian faults from Paleozoic faults. Relatively late Precambrian faults may have moved again in the Paleozoic. Where discordant relationships are encountered in the field and covered areas prevent observation of critical areas, the structure has generally been interpreted as disharmonic folding. Other likely causes of discordance are Precambrian faults and angular unconformities. Faults may also be present in some places where lateral discontinuity of strata is interpreted as Precambrian sedimentary facies change.

Three thrust faults shown in the southeastern part of the plate 1 area and a vertical shear zone with right-handed strike-slip displacement in the southwestern part (Click quadrangle) are Precambrian structures. The thrusts are distinct from the Paleozoic normal faulting; maximum compression was more nearly horizontal than vertical. There is some quartz mineralization possibly related to the Hardin Hills thrust (McCandless, 1957, p. 31); this is rare along Paleozoic faults. Rock units were displaced laterally with rotation of lineation (drag) into the fault trend of the southwestern shear zone (Clabaugh and Boyer, 1961, p. 14). This requires horizontal movement and horizontal orientation of principal stress, which is atypical of the Paleozoic faulting.

McCandless (1957, p. 57-61) first proposed the existence of thrust faults in the southeastern part of the Llano region to explain the distribution of the rock units he mapped. He believed that the two east-dipping faults originated as a result of décollement in graphite schist of the Honey Creek Formation. Apparently, amphibolite bodies in the hanging walls of these two faults resisted folding and led to the dislocations at their western margins. The west-dipping (Hardin Hills) thrust can be traced for several miles, from the central part of the area almost to the southeastern Paleozoic border fault. Northeast-southwest shortening caused by the Hardin Hills thrust is at least 1 mi (1.6 km).

The shear zone in the Red Mountain area can be traced for about 3 mi (4.8 km). It trends roughly north to slightly northwest and affects the rocks for a maximum outcrop width of about 700 ft (210 m). Weathering of the brecciated rocks in the fault zone resulted in a linear depression along its trace. Geologic contacts are offset about 600 ft (180 m) in a right lateral sense.

Foliation, Lineation, and Minor Structure

In the southeastern Llano region foliation is generally parallel to original bedding; that is, planar structures such as fissility, schistosity, and banding are parallel to lithologic contacts and bend around the major folds. Because foliation curves around folds and dips at various angles, it could not have originated at a constant angle to the maximum principal stress or with some consistent relationship to axial planes of folds. Slip along flexure surfaces appears to explain the schistosity in these rocks. Flexural slip explains the foliation, the two directions of lineation, and the bending of foliation around major fold axes. The *b*-lineation developed by rotation and slip of adjacent layers over one another forced nonplastic minerals into an orientation normal to the direction of slip. Lineations developed in the *a* direction of transport as a slickensides effect.

Axial plane foliation, in addition to regional foliation, is seen in areas the size of a hand specimen or in single outcrops at several localities.

Lineation appears as streaks, crenulations, striations, and ridges on rock surfaces (pl. 2, a and b). The various types of lineation are caused by (1) intersection of s-planes, (2) preferred orientation of prismatic minerals (particularly hornblende), (3) minor folds and crinkles, (4) aligned trains of mineral concentrations, (5) stretched minerals (such as quartz and feldspar in some of the Red Mountain Gneiss), and (6) rodding in hornblende schist, where shear couples set up during flexure folding caused fracturing and rotation of large fragments of schist. Nearly all lineation is parallel to the major and drag fold axes. Rarely it occurs in directions neither parallel nor perpendicular to fold axes. In a few places where two lineations are present,

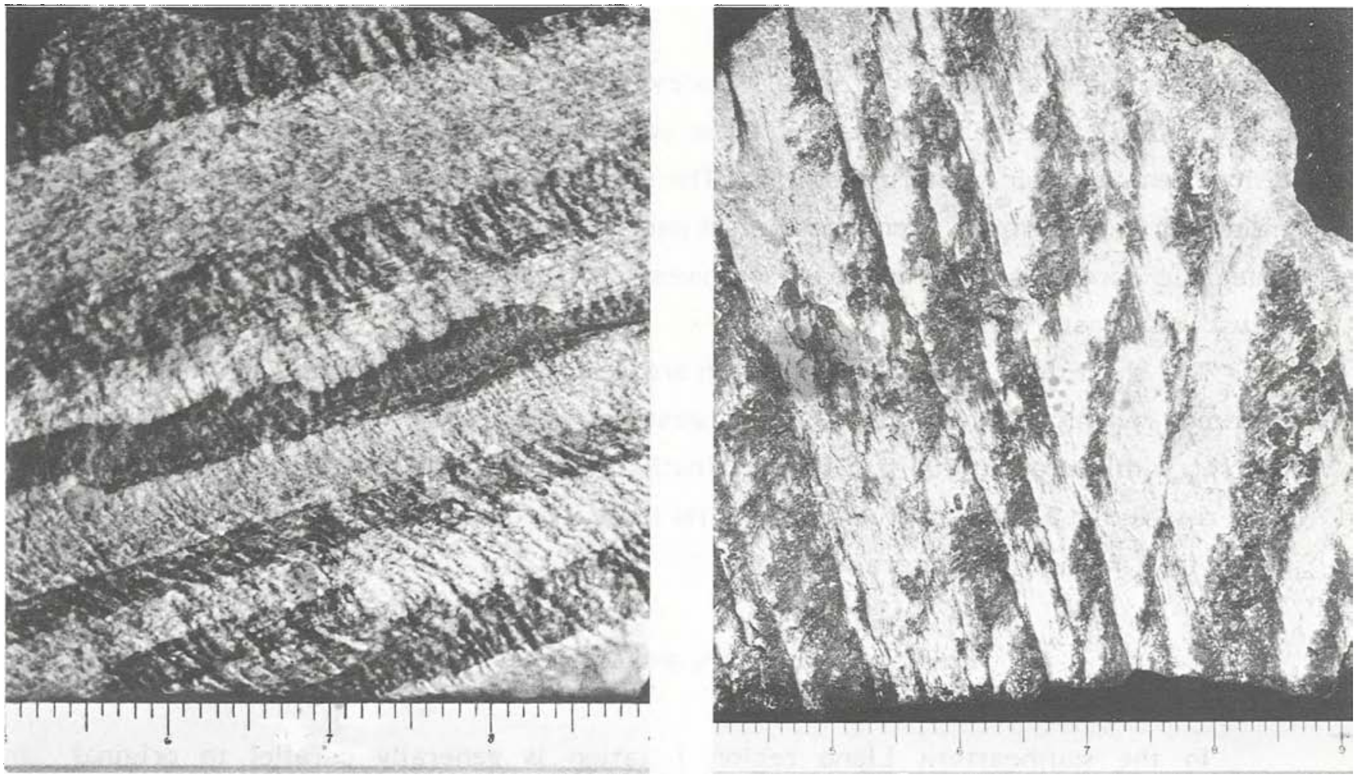


Plate 2, a and b. Two lineations in graphite-mica schist. Honey Creek Formation, Packsaddle Schist. Scale is inches.

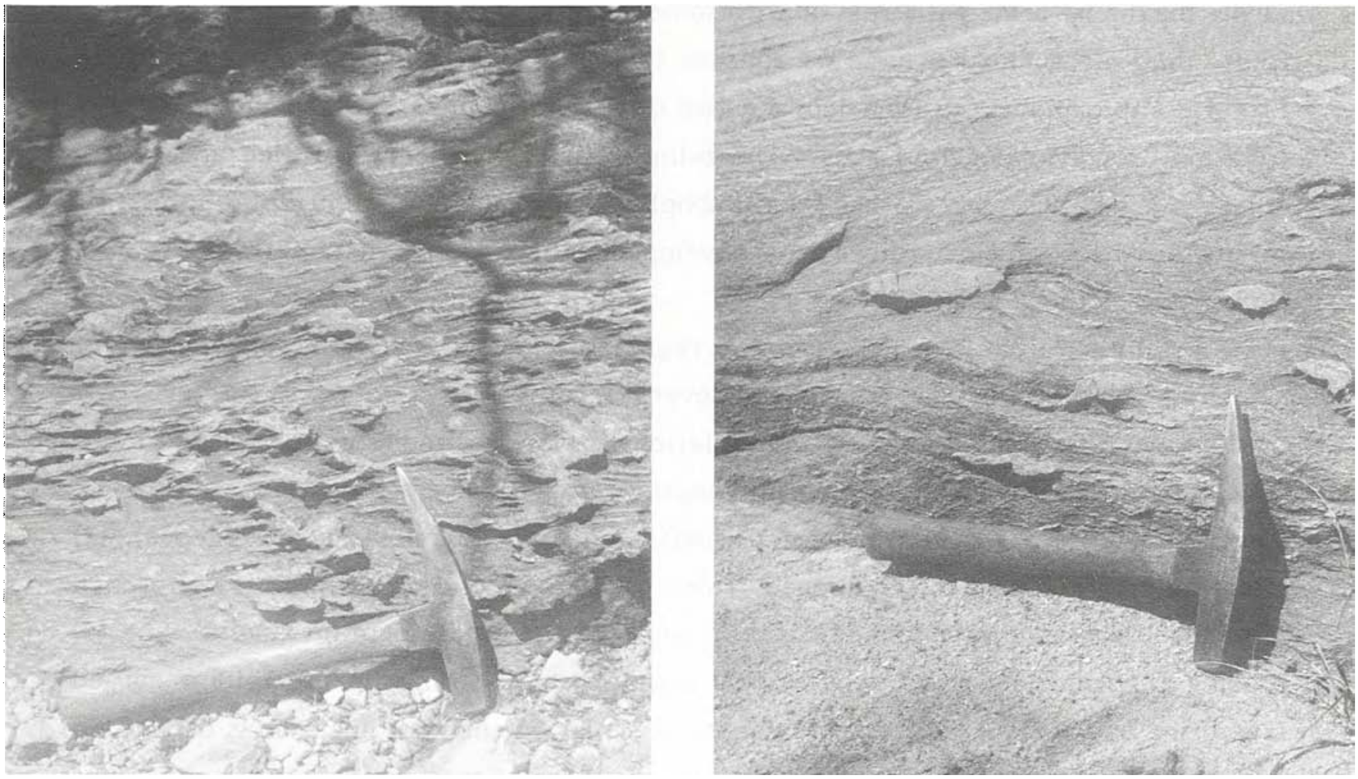


Plate 2, c and d. Small-scale folding and boudinage in leptite. Rough Ridge Formation.

successive foliation surfaces contain first one and then the other. Multiple lineations are more commonly seen in graphite schist than in any other rock type.

Drag folds, small-scale folds apparently formed as subordinate features parallel to and contemporaneous with major folds, are common structures in the southeastern Llano region. They range in amplitude from less than 1 mm to tens of feet. Most small-scale folds are parallel to the major folds; their axes form *b*-lineations. Other small-scale folds are perpendicular, or nearly perpendicular, to the major fold axes (forming *a*-lineations) or lie at some intermediate angle. Many of these minor folds are related to Town Mountain Granite intrusion. They are more common in marble, graphite schist, hornblende schist, and mica schist, than in the more competent leptite and quartz-feldspar gneiss. Boudinage occurs in places with small-scale folding. Plate 2 (c and d) shows a type of combination folding and boudinage in quartz-feldspar-biotite schist of the Rough Ridge Formation. Competent layers were ripped apart during folding, and the isolated pieces now project as knobs from the outcrop.

PETROGRAPHY

Valley Spring Gneiss

Pink quartz-feldspar gneiss and leptite are typical of the Valley Spring Gneiss. The average rock contains 30 percent microcline, 30 percent quartz, and 34 percent plagioclase (oligoclase and andesine). Accessory minerals include sphene, apatite, magnetite-ilmenite, and epidote. Average grain size is 0.35 mm. The gray unit B gneiss averages 63 percent plagioclase, 25 percent quartz, 8 percent biotite, and 3 percent hornblende. The augen in the augen gneiss layer near the top of the Valley Spring are microcline in the Honey Creek area and plagioclase several miles to the northwest.

Packsaddle Schist

Marble and Calc-Silicate Rock

All of the marble in the Honey Formation contains at least 35 percent calcite or dolomite, and calc-silicate rock contains at least 65 percent calcium silicate minerals. Most of the rock has a mosaic texture and weakly developed foliation or no foliation. Mineral composition is all calcite, mixtures of calcite and tremolite, or all tremolite (pl. 4) or diopside. Plagioclase (commonly labradorite), microcline, quartz, graphite, and limonite are present in small quantities. Less common accessories include sphene, epidote, muscovite, zircon, ilmenite-magnetite, actinolite, brucite, humite, talc, scapolite, pyrite, and chlorite. Nearly pure calcite marble is coarser grained than calc-silicate rock.

Near granite and pegmatite bodies, contact metamorphosed rock commonly contains coarse idocrase and wollastonite. A talc-scapolite-quartz-plagioclase contact metamorphic assemblage occurs in the northwest corner of the Cap Mountain quadrangle, and a calcite-antigorite assemblage occurs northeast of Packsaddle Mountain, in the Kingsland quadrangle.

Amphibole Schist

Amphibole schist is found throughout the Packsaddle except in the Rough Ridge Formation. The common amphibole is blue-green hornblende, but a few samples contain tremolite or actinolite. Most of the rock is very fine grained, and some is phyllite. Average mineral composition is 40 percent hornblende, 30 percent quartz, and 30 percent plagioclase (oligoclase-andesine). In the Sandy Formation, microcline is slightly more abundant than plagioclase. Minerals present in small quantities include diopside, epidote, sphene, and magnetite.

Graphite Schist

Graphite schist is a distinctive rock in the Honey Formation, and marble is everywhere associated with graphite schist. Commonly schist and marble form a layered sequence, but in some places only minor amounts of marble are present. The thick uppermost section of graphite schist is gradational into very fine grained graphite-hornblende and hornblende schist, phyllite, and hornfels.

Quartz is the predominant mineral in most samples; graphite content ranges from a few percent up to 30 percent. In a few samples untwinned plagioclase is more abundant than quartz. Common minor constituents are muscovite and sericite, biotite, and pyrite. Near State Highway 71, in the central part of plate 1, microcline averages 20 percent in the graphite schist.

Graphite schist that crops out in a band about 3 mi (4.8 km) long extending north from Sandy Creek, near and roughly parallel to the edge of the Kingsland pluton (Town Mountain Granite), contains abundant large chiastolitic andalusite porphyroblasts (pl. 3a). The distribution of andalusite is sporadic, and it is partly or totally replaced

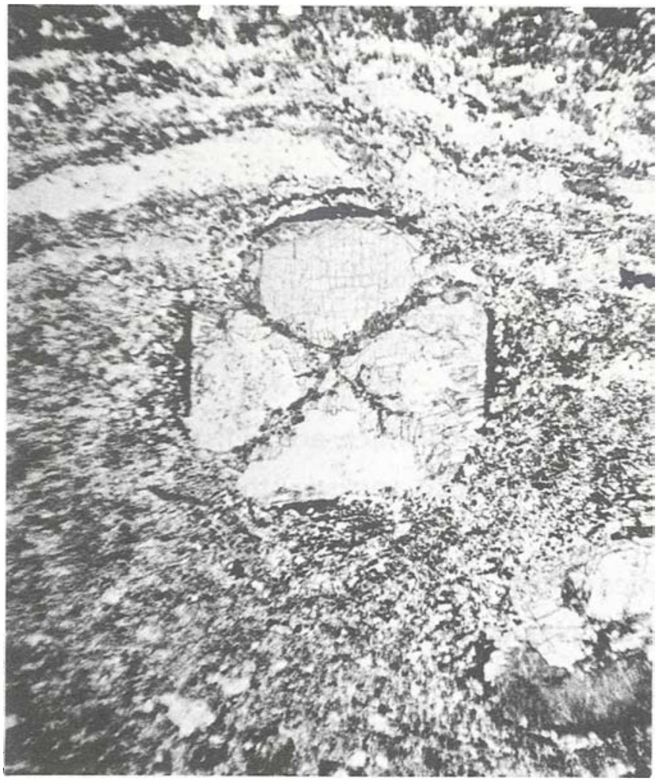


Plate 3a. Chiastolitic andalusite porphyroblast in graphite schist. Crystal side is 1 mm long. Crossed nicols. Honey Formation, Packsaddle Schist.

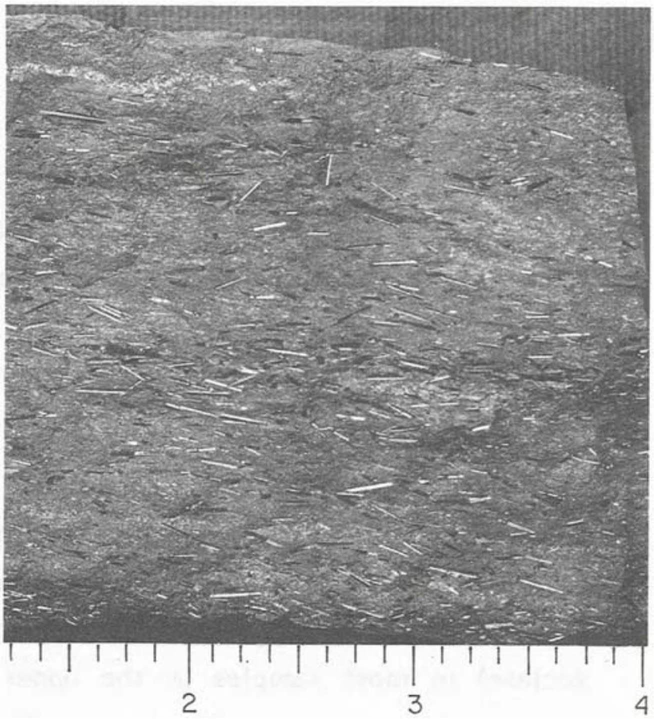


Plate 3b. Tourmaline, forming lineation in graphite schist. Honey Formation. Scale is inches.

Plate 3c. Cordierite porphyroblasts in graphite schist. Honey Formation. Scale is inches.

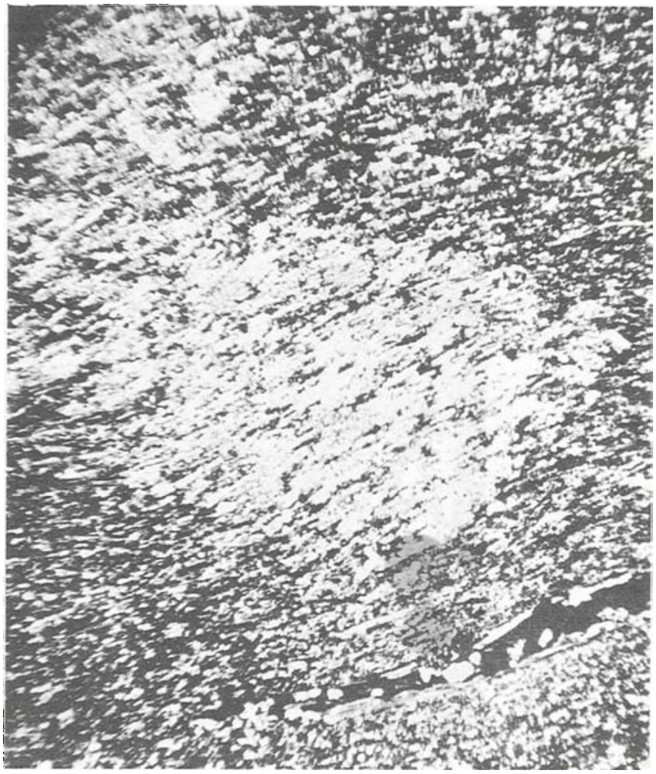


Plate 3d. Cordierite porphyroblast in graphite schist. Long diagonal of crystal is 2 mm. Crossed nicols. (Thin section of specimen in c.)

by sericite in nearly all samples. The andalusite occurs in aggregates and single slender prisms up to 4 inches (10 cm) long. Black to dark-brown tourmaline is abundant locally (pl. 3b), particularly near contacts with pegmatite.

Cordierite porphyroblasts were tentatively identified in two samples of graphite schist from the south-central part of the plate 1 area (pl. 3, c and d).

Leptite and Quartz-Feldspar (-Mica) Schist

Granoblastic quartz-feldspar rocks, or leptite, many of which are indistinguishable from metaquartzite in the field, and quartz-feldspar rocks with poorly to moderately well developed schistosity occur in all formations of the Packsaddle. Commonly, these rocks grade into gneiss and mica schist.

Microcline is slightly more abundant than plagioclase (mostly untwinned oligoclase) in most samples in the upper three formations of the Packsaddle, but plagioclase is more abundant in the Honey Formation. Accessory minerals include garnet, epidote, sulfides, biotite, amphibole, zircon, apatite, and sphene. In places near contacts with granite, sillimanite occurs in fine-tufted masses and in prisms up to 4 cm long and 5 mm wide (pl. 4, pl. 5a). Sillimanite and andalusite occur together 100

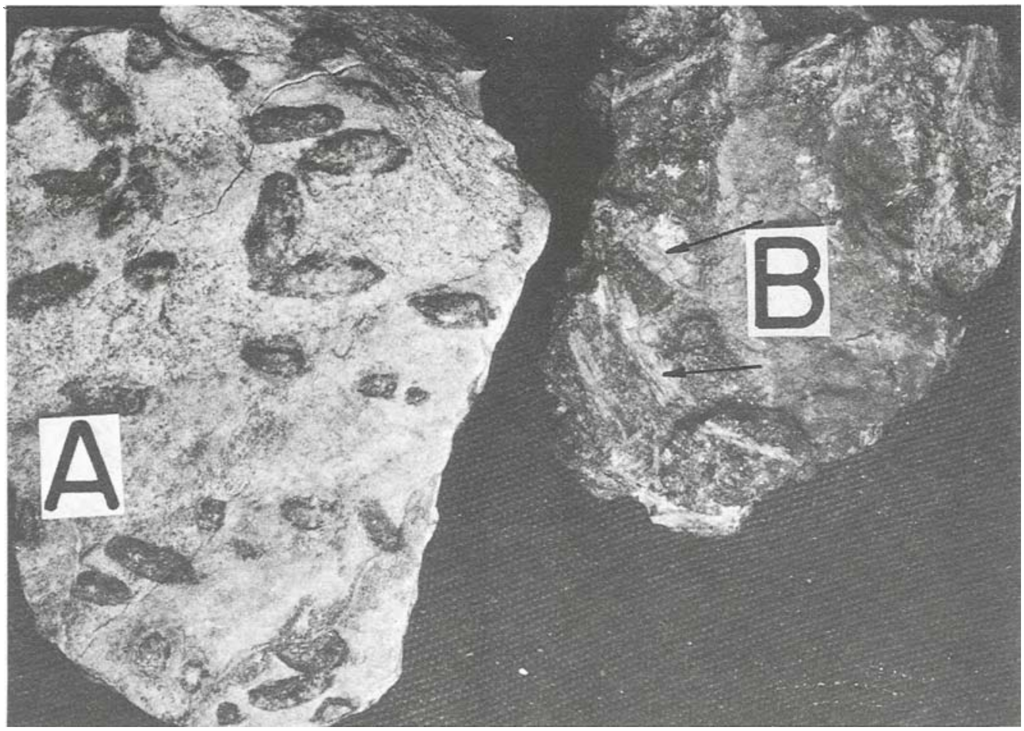


Plate 4. Cordierite porphyroblasts in muscovite schist (A) and sillimanite porphyroblasts in quartz-feldspar-mica schist (B). Honey Formation.

ft (30 m) from the granite contact on the south side of Sandy Mountain (Dunman Mountain quadrangle). Tourmaline is abundant in some of these contact-metamorphosed rocks.

The Rough Ridge Formation contains gray, massive, poorly foliated quartz-feldspar rock with abundant lens and pod segregations of epidote-quartz, epidote-quartz-hornblende, epidote-garnet-calcite, and quartz-actinolite. In some of these rocks, such as those forming Rough Ridge itself, hornblende is abundant (up to 20 percent); biotite is prominent but less abundant than hornblende.

Mica Schist and Gneiss

Mica schist is found throughout the Packsaddle. A thick muscovite schist unit in the upper half of the Honey Formation, west of Packsaddle Mountain (Click quadrangle), in several places contains porphyroblasts of cordierite, pyrite, andalusite, garnet, and tourmaline. These minerals may have formed in response to hydrothermal solutions from nearby quartz veins; no granite or large pegmatite bodies crop out in the vicinity of these rocks. The cordierite occurs as black ovoids, 0.5 to 1 inch (1 to 2.5 cm) long rimmed by biotite (pl. 4). Small tourmaline grains are abundant both in the matrix and as inclusions in cordierite. Crystals of andalusite up to 10 inches (25 cm) long occur at two localities where quartz veins also containing andalusite cut the schist. In one outcrop the andalusite is associated with small euhedral garnet porphyroblasts. Andalusite porphyroblasts also occur in muscovite schist in the Rough Ridge Formation.

Biotite gneiss forms a prominent unit in the upper third of the Rough Ridge Formation. The base of this gneiss unit contains abundant large (up to 4 inches [25 cm]) cordierite porphyroblasts (pl. 5b). The rock is crinkled, and a second foliation is developed parallel to the axial planes of the small crinkle-folds. Some cordierite porphyroblasts contain inclusions showing both foliations; others have curved inclusion trains, indicating rotation during growth. Burnitt (1961, p. 35-37, 42-44) described mica-cordierite schist and biotite- sillimanite-andalusite schist from the Click Formation. The latter unit occurs near a sill of Red Mountain Gneiss and may be a contact metamorphic product of granite intrusion.

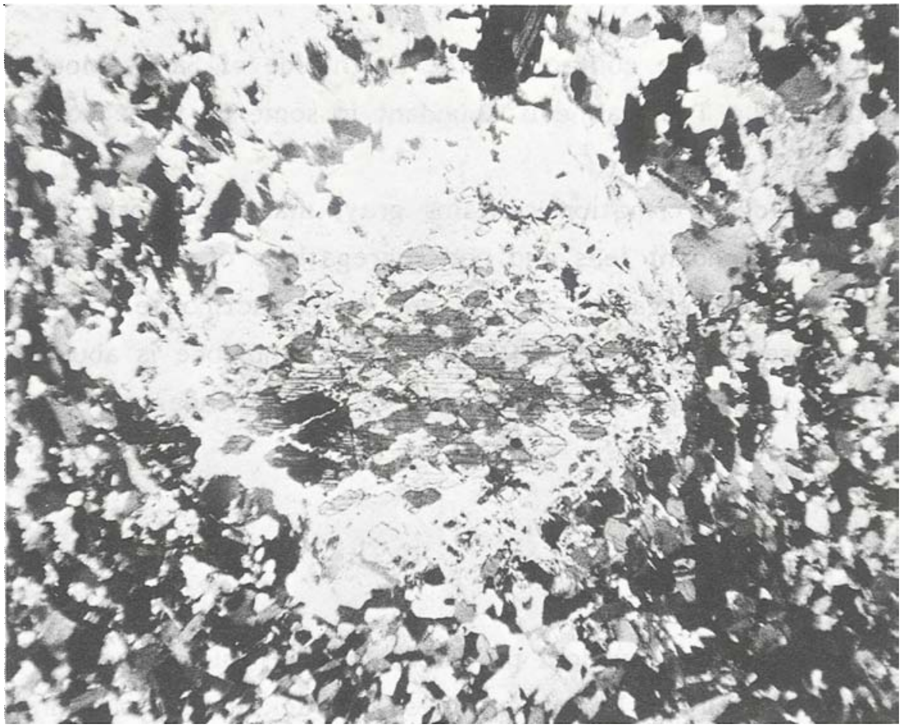


Plate 5a. Sillimanite porphyroblast in quartz-feldspar-mica schist. Long diagonal of the crystal is 1.8 mm. Crossed nicols. (Thin section of specimen B in pl. 4.)

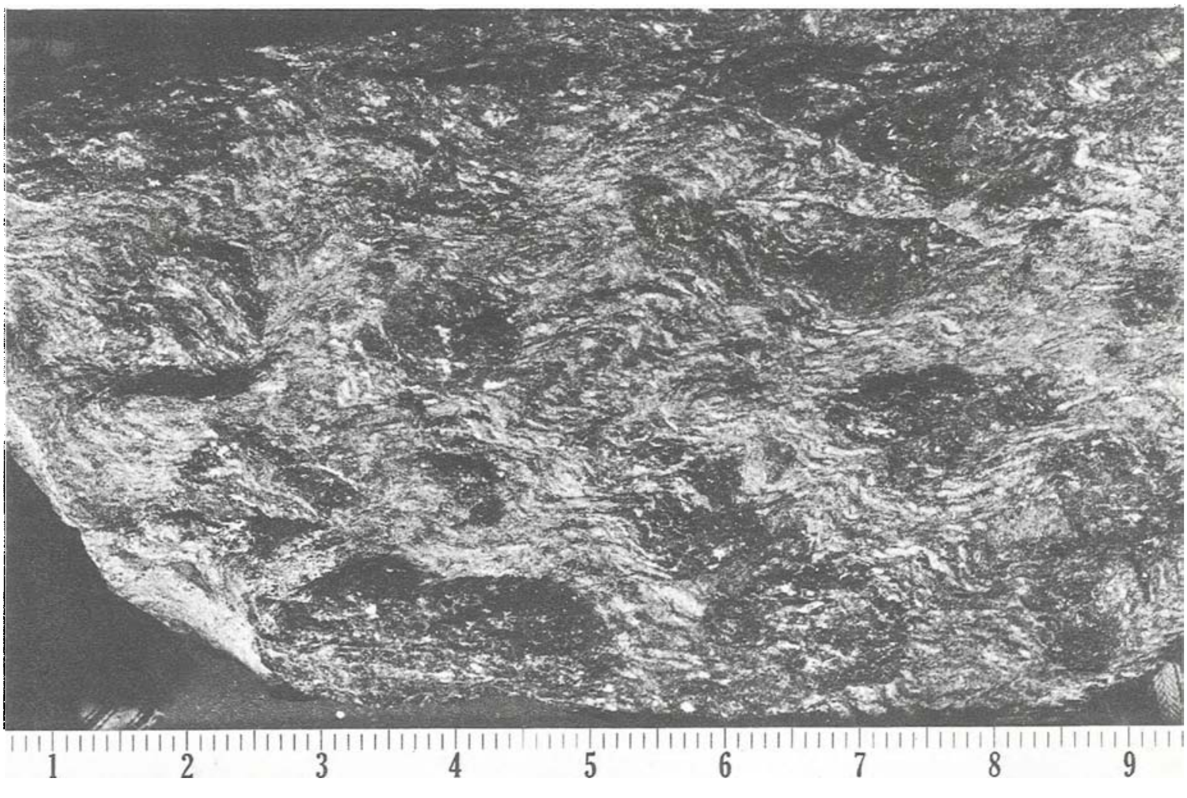


Plate 5b. Cordierite porphyroblasts in crinkled biotite gneiss. Rough Ridge Formation. Scale is inches.

Metamorphosed Igneous Rocks

Amphibolite

Bodies of amphibolite derived from metamorphism of gabbro and dolerite are scattered throughout most of the map area. The largest masses are at Sunrise Beach and Green Mountain (Dunman Mountain quadrangle) and at the mouth of Coal Creek (Click quadrangle). The greatest concentration of amphibolite bodies is in the southwestern corner of the area, roughly between Coal and Comanche Creeks and north of the Coal Creek Serpentine body (Blowout quadrangle). These are mostly elongate dike-like and sill-like bodies, some as much as 2 mi (3.2 km) long. Some amphibolite bodies are resistant to erosion and rise as hills, such as Green Mountain and Mesquite Hill (Dunman Mountain quadrangle). Other amphibolite weathers to form low uplands. Good natural exposures are rare. In many places the clue to the presence of an underlying amphibolite body is rusty-colored amphibolite rubble on the surface or a characteristic deep-reddish-brown soil.

Some amphibolite bodies in the southeastern Llano region show crosscutting field relationships or relic igneous features and are clearly meta-igneous. All or most of the other bodies are considered to be meta-igneous because they are lithologically similar to the proved meta-igneous bodies. In the southwestern part of the region some amphibolite bodies have distinctly igneous features, such as euhedral plagioclase phenocrysts or pseudomorphous mosaics of fine plagioclase grains. Some of the bodies decrease in grain size toward the margins, and others have massive cores and foliated margins.

Hornblende, highly pleochroic from blue green to nearly colorless, is the chief mineral constituent in most of the amphibolite. Diopside is the chief or only mafic mineral in a few samples. Untwinned andesine is the second most abundant mineral in most of the amphibolite. Other less common constituents include microcline, quartz, epidote, and scapolite. Sphene, magnetite, apatite, and chlorite are accessory minerals. The plagioclase is less calcic than in gabbro, so perhaps calcium lost from original plagioclase during metamorphism went into making epidote and scapolite. However, a few bodies of amphibolite, including the one at Mesquite Hill, contain plagioclase as calcic as labradorite.

Big Branch Gneiss

Big Branch Gneiss crops out in the southern part of Click quadrangle and in Blowout quadrangle; it is the predominant Precambrian rock of northeastern Gillespie County and northwestern Blanco County. Crosscutting field relationships and relic igneous textures leave no doubt as to its igneous origin. Barnes (1945, p. 56-57) gave a chemical analysis of the gneiss and described it as a quartz diorite. Numerous Packsaddle inclusions lie in the gneiss. Barnes considered it a somewhat more acidic intrusive igneous rock that assimilated substantial amounts of Packsaddle rock during emplacement.

The rock is gray, fine to coarse grained, poorly to well foliated, and averages about 45 percent plagioclase (oligoclase), 20 percent quartz, 15 percent biotite, 8 percent hornblende, and 2 percent epidote. Sphene, apatite, and zircon are important accessory minerals. Most plagioclase grains are subhedral and twinned. The larger crystals are commonly fringed by a mosaic of fine quartz and feldspar, and commonly are bent and granulated. Many grains are zoned, with saussuritized calcic cores. Recrystallized plagioclase is more sodic than relic igneous grains. Zircon occurs as long idiomorphic crystals and as stubby, hackly crystals. Barnes (1945, p. 57) considered the latter to be remnants of assimilated Packsaddle rocks.

Near Red Mountain, in Click quadrangle, the Big Branch is a metasomatized augen gneiss (Clabaugh and Boyer, 1961, p. 11). Pink microcline porphyroblasts make up 20 to 40 percent of the rock. The addition of potassium to the rock probably occurred at the time of Red Mountain granite intrusion.

Red Mountain Gneiss

Red Mountain Gneiss is metamorphosed granite, which occurs in concordant and crosscutting bodies, contains xenoliths of Packsaddle schist, and shows both relic igneous texture and contact metasomatic effects. It is granoblastic to strongly foliated. Much of the rock that is poorly foliated possesses a strong lineation caused by either stretched quartz and feldspar rods or flattened quartz and feldspar flakes. A typical sample contains 45 percent microcline, 35 to 40 percent quartz, 10 to 15 percent oligoclase, 5 percent biotite, and accessory magnetite, muscovite, apatite, sphene, and zircon.

Red Mountain Gneiss is most abundant in a swarm of tabular bodies that pinch and swell and are cut by faults, but persist across the southern two-thirds of Click quadrangle, and in Blowout quadrangle probably curve eastward under cover of Paleozoic rocks to emerge as the east-west-trending sill in the Dunman Mountain and Howell Mountain quadrangles. These sills form resistant ridges such as Post Oak Mountain, Red Mountain, and Granite Knob.

Several bodies of meta-igneous rock cut Valley Spring Gneiss. Average composition of the meta-igneous rock is 40 percent andesine, 35 percent microcline, and 20 percent quartz. It is distinguished from Valley Spring Gneiss by its irregular jointing, crosscutting relationships, and lack of well-developed foliation. These rocks are probably related to the Red Mountain intrusives. Another rock type that is probably genetically related to Red Mountain Gneiss is meta-aplite, which forms small bodies in the southwestern part of the area. The meta-aplite contains 50 to 60 percent albite-oligoclase and has granophyric and myrmekitic textures.

Hornblende Metadiorite

A mass of hornblende-plagioclase rock, called hornblende granite by Paige (1912, p. 5) and metasomatized metagabbro by Burnitt (1961, p. 60-62), forms a small hill about 3,000 ft (900 m) southeast of Click (Click quadrangle). Near the borders of the mass the plagioclase is largely replaced by microcline. The body is irregular but roughly conformable with the surrounding rocks; it is cut to the east by a shear zone and thins and interfingers with metasedimentary rocks to the west. Albite-oligoclase makes up 70 to 90 percent of the usual sample, and hornblende is the other major constituent. The plagioclase occurs in coarse grains, almost all twinned. Portions of many grains are partly replaced by a mosaic of fine untwinned plagioclase. The hornblende occurs in stubby prisms with highly shredded ends. Rarely the hornblende occurs as rims on augite grains. Quartz averages 5 percent of the rock, and sphene and associated ilmenite are prominent accessories.

Coal Creek Serpentine

A large mass of serpentine underlies low, rough, nearly bare hills in the Blowout and Willow City quadrangles. Platy antigorite and structureless serpentine form a network texture with little evidence of postserpentinization deformation. Many pseudomorphs after olivine and some possibly after amphibole are present. Magnetite is the chief accessory mineral. The presence of chromite and zaratite and relatively high percentages of chromium and nickel in the rock (Barnes and others, 1950, p. 10-11) indicate an ultramafic parent rock. Xenoliths of Packsaddle Schist and Big Branch Gneiss (Barnes, 1945, p. 75) and the general outcrop pattern of the serpentine show that the parent rock was intrusive.

Soapstone

Most of the soapstone occurs in the southwestern part of the Click quadrangle and southward in the Blowout quadrangle, and is associated with amphibolite and serpentine. It was originally ultramafic intrusive rock. Talc, chlorite, tremolite, and accessory magnetite are the dominant minerals of the soapstone samples studied by Burnitt (1961, p. 68). Small amounts of quartz, plagioclase, epidote, apatite, zircon, and sphene are common; anthophyllite makes up 30 percent of one sample.

Mafic Dikes

Slightly metamorphosed, diabasic hornblende-plagioclase dike rocks are found in various places. None of the bodies are very large; the longest mapped is about 1 mi (1.6 km). Zoned plagioclase (An_{33} at grain edges) phenocrysts up to 10 mm long occur in a few samples. The hornblende is largely replaced by chlorite.

Igneous Rocks

Melarhyolite

A dike-forming, dark-gray to black, very tough, slightly porphyritic and very fine grained rhyolitic rock was first described in the Llano region by Paige (1912, p. 5). He mapped two dark aphanitic dikes which he called spherulitic mica felsite and hornblende-mica felsite. Paige classified these rocks with the metamorphosed mafic and ultramafic intrusives, and "hornblende-soda granite" of the Click vicinity as older than the granites.

Most of the melarhyolite occurs in the Click and Dunman Mountain quadrangles; the longest dike is about 8 mi (12.8 km). The dark color of the rock results from its 15 to 30 percent biotite content (including some amphibole in a few samples) and fine grain size. A few phenocrysts of quartz, anorthoclase, albite, and microcline lie in an aphanitic and spherulitic matrix of quartz, feldspar, biotite, amphibole, and opaque minerals.

Although crosscutting relationships indicate that melarhyolite is the youngest, or one of the youngest, of the Precambrian rocks, some of the biotite grains show a preferred orientation at an oblique angle to the dike walls and parallel to the foliation of the adjacent schist. This orientation indicates the rock was affected by stresses accompanying the final stages of regional metamorphism, or by later stresses resolved along the foliation of the enclosing schist.

Town Mountain Granite

Town Mountain Granite has a medium- to coarse-grained groundmass of quartz, feldspar, and biotite, and an abundance of large pink microcline and white plagioclase and perthite phenocrysts. Within individual masses the rock type ranges from granite to granodiorite, quartz monzonite being the most common rock. Average grain size of the matrix is 3.5 mm; phenocrysts average about 20 mm long. Much of the granite has rapakivi texture.

Elongate inclusions of metamorphic rock are numerous near and parallel to the borders of the granite masses. Contacts between the granite and xenoliths are very sharp.

The granite is commonly deeply weathered and forms areas of low relief. Where fresh granite is exposed, it generally crops out as low, rounded hills with exfoliation shells and slightly raised ridges of pegmatite and aplite.

In many places within the outcrop area of Town Mountain Granite there is a finer grained, nonporphyritic, light-gray granite. Its mineral composition is similar to that of Town Mountain, but locally it contains more biotite.

Pegmatite and Aplite

Pegmatite bodies, many of which are probably late magmatic differentiates of Town Mountain magma, occur throughout the map area. They are abundant near granite contacts; some occur partly or completely within the granite. The pegmatites are mainly tabular, straight, and steeply inclined; they range from less than 1 inch to 60 ft (2.5 cm to 18 m) thick and from a few inches to about 5,000 ft (1,500 m) long. Many of them form low resistant ridges. Where land has been cleared around them they stand out as conspicuous brush lines on aerial photographs. They appear to be parallel to joint sets in the host rock. Aplite dikes are common within the granite bodies and also occur in smaller numbers in the metamorphic country rock.

Large and mineralogically complex pegmatites occur only within Packsaddle rocks, near Town Mountain contacts. Some of these contain tourmaline, topaz, almandite garnet, spessartite garnet, fluorite, beryl, apatite, sphene, molybdenite, cassiterite, corundum, and stilpnomelane. The Kiam pegmatite on Honey Creek (Cap Mountain quadrangle), which in the 1930's had more than 500 ft (150 m) of underground workings, contains native bismuth and bismuthinite (Stenzel and Barnes, 1939, p. 916-919).

Much of the pegmatite is quartz and perthitic microcline, in places graphically intergrown: sugary albite and mica are common additional constituents. Quartz-feldspar pegmatite bodies are extremely numerous within the Valley Spring Gneiss in the northern part of the study area. Many of the small and mineralogically simple bodies probably formed more or less in place by anatexis during metamorphism.

Quartz Veins and Masses

Veins of cloudy to milky quartz with variable amounts of amphibole, epidote, andalusite, garnet, cordierite, tourmaline, and pyrite are abundant throughout the study area. The veins and irregular masses are resistant and form topographic highs.

The quartz bodies are probably hydrothermal derivatives of the Town Mountain magma. However, some of them may be products of local metamorphic mobilization and segregation. Muscovite schist in the lower part of the Rough Ridge Formation on Sandy Creek contains two distinct types of quartz bodies, which illustrate products of the two modes of origin: (1) milky quartz veins with sharp crosscutting relationships to the schist (hydrothermal), and (2) pale-pink and violet quartz in small irregular pods roughly parallel to foliation in the schist (metamorphic segregation).

METAMORPHISM

Metamorphic mineral assemblages in the southeastern Llano region fall mostly in the almandine-amphibolite facies of regional metamorphism as defined by Turner

(Turner and Verhoogen, 1960, p. 544-553). Typical mineral assemblages are

Pelitic assemblages
(1) Quartz-muscovite-biotite-plagioclase(-cordierite)
(2) Quartz-muscovite-biotite-plagioclase(-microcline)

Quartz-feldspathic assemblage
(3) Quartz-microcline-plagioclase-biotite-muscovite(-epidote-hornblende)

Basic assemblages
(4) Hornblende-plagioclase(-epidote-diopside-scapolite-sphene-microcline)
(5) Diopside-plagioclase

Calcareous assemblages
(6) Tremolite-diopside(-calcite)
(7) Calcite-tremolite (Quartz, plagioclase, microcline, muscovite, and possibly phlogopite are present in small amounts in many of the calcareous rocks)

The temperature and pressure conditions corresponding to this rank of regional metamorphism were estimated by Turner to be 550° to 750° C and 4,000 to 8,000 bars. Assemblages were transitional to the hornblende hornfels facies of contact metamorphism corresponding to pressures as low as 3,000 bars. The presence of sillimanite rather than staurolite or kyanite, and of muscovite and microcline rather than orthoclase in pelitic and quartz-feldspar rocks indicates that the rocks are in the sillimanite-almandine-muscovite subfacies. Evidence that the rocks generally achieved equilibrium during regional metamorphism includes (1) lack of reaction rims, (2) fairly consistent mineralogy in similar rock types, and (3) numbers of mineral phases consistent with the equilibrium requirements of the mineralogical phase rule.

Plagioclase compositions in pelitic schists, amphibolite, and calc-silicate rocks closely fit the range specified by Turner for the sillimanite-almandine-muscovite subfacies. However, the presence of andalusite and cordierite and the relative rarity of garnet are anomalous in this facies as defined and, considered with the other minerals present, point toward high temperature and low pressure. Evans and Leake (1960, p. 361) encountered similar relationships in Connemara rocks of Ireland, where there are widespread occurrences of cordierite, sillimanite, andalusite, and, in the basic rocks, amphibole (low pressure) instead of almandine (high pressure). Miyashiro (1961, p. 277) proposed that metamorphic belts are characterized by a series of facies corresponding to a certain range of rock pressure. Regional metamorphic assemblages of the southeastern Llano region correspond with Miyashiro's amphibolite facies of the andalusite-sillimanite type series (series formed lowest rock pressure).

Contact metamorphism near granite and pegmatite bodies is particularly noticeable in the marble beds, some of which were entirely converted to wollastonite and idocrase. A common assemblage is idocrase-wollastonite-diopside-plagioclase-calcite; wollastonite-calcite and scapolite-talc rocks have also been found. Sillimanite occurs in pelitic rocks near granite contacts and in some areas is associated with andalusite. Sims (1957, p. 44) found the assemblage andalusite-sillimanite-orthoclase-cordierite-biotite-quartz. Chiastolitic andalusite is abundant in a belt of graphite schist which parallels the granite contact about 1,000 ft (300 m) from it, whereas andalusite is absent from graphite schist elsewhere.

Tourmaline is a common metasomatic mineral related to the emplacement of the igneous and hydrothermal bodies. Addition of potassium (K) was quantitatively the most important metasomatic activity associated with Town Mountain Granite intrusion. Products of K-metasomatism are microcline porphyroblasts and K-spar mantles on plagioclase and conversion of andalusite, sillimanite, and cordierite to muscovite. Introduction of potassium into wall rocks at the time of intrusion of Red Mountain granite led to development of microcline augen gneiss in Big Branch Gneiss (Clabaugh and Boyer, 1961, p. 11, 15) and of augen schist in Packsaddle rocks. Also some cordierite, andalusite, and sillimanite in nearby rocks are probably products of Red Mountain igneous activity. Hydrolysis associated with late-stage Town Mountain igneous activity produced muscovite from microcline, serpentine and brucite from forsterite, and tremolite from diopside.

Slight retrograde metamorphism produced chlorite from biotite and amphibole and epidote from plagioclase.

GEOLOGIC HISTORY

The oldest rocks known in the southeastern Llano region were sediments or lavas, pyroclastics, and sediments. The rocks were metamorphosed, folded and faulted, and intruded by magmas of varied composition. The metamorphism and deformation probably occurred in a single episode and at relatively high temperature and low pressure. Present thickness of the metasedimentary (or metavolcanic plus metasedimentary) rocks is at least 28,000 ft (8,400 m). Including rocks outside of the present area of study, the thickness of original sediments probably greatly exceeded this figure.

Gabbro was the earliest intrusive rock. Gabbro-dolerite intrusion probably occurred at different times during much of the regional metamorphism. Quartz diorite intrusion (Big Branch Gneiss) was followed by granite (Red Mountain Gneiss). Ultramafic material, which later became Coal Creek Serpentine and bodies of talc and soapstone, was emplaced in this general period. Finally, in the last stages of regional metamorphism, about 1,050 m.y. ago, great masses of granite (Town Mountain Granite) and their pegmatite and aplite invaded the metamorphic rocks. Temperature rose in country rock near granite contacts, and solutions from the granite permeated much of the country rock, causing both local and pervasive metasomatism. Stresses related to granite intrusion caused modification of structure in the country rock. The last products of magmatic activity were melarhyolite and possibly mafic dikes.

The Precambrian rocks were eroded to a surface of moderate relief, and Paleozoic sedimentation began in middle Cambrian time (Hickory Sandstone). The oldest sediments are composed of debris from the Precambrian rocks now exposed. Late Paleozoic (Pennsylvanian?) arching of the Llano Uplift caused high-angle normal faulting, with many of the faults trending northeast. Following erosion that accompanied the late Paleozoic uplift, Cretaceous sediments covered Precambrian rocks of the region, but they were largely stripped off after Balcones faulting and uplift. Quaternary sediment lies along the streams, and soil covers much of the rock in the area today.

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APPENDIX--COMPOSITE STRATIGRAPHIC SECTION

Generalized from sections measured by D. N. Blount and R. V. McGehee in Honey Creek and one of its branches, Cottonwood Creek and one of its branches, Sandy Creek, and on part of the John Pearson ranch, southwest of Click. These are type sections for the formations of the Packsaddle Group (McGehee, 1963, p. 220-242).

	Thickness	
	ft	m
Packsaddle Schist		
Click Formation (top not present in area of study)		
Quartz-mica schist; layers of Red Mountain Gneiss (not included in thickness figure)	1300	395
Leptite; traces of quartz-feldspar-mica schist and amphibole schist; layers of Red Mountain Gneiss in upper part (not included in thickness figure)	1620	495
Leptite and actinolite schist	610	185
Rough Ridge Formation		
Leptite; some quartz-feldspar-biotite schist and hornblende schist	580	175
Biotite gneiss, with large cordierite porphyroblasts in lower part; some leptite in upper part	950	290
Leptite	420	130
Quartz-feldspar-muscovite schist	380	115

	Thickness	
	ft	m
Leptite, gray, massive; some layers of quartz-feldspar-biotite schist	1590	485
Quartz-feldspar-mica schist and muscovite schist	420	130
Leptite and quartz-feldspar-mica schist; some quartz-muscovite schist; layers of Red Mountain Gneiss in basal part (not included in thickness figure)	1000	305
Sandy Formation		
Hornblende schist	790* (580;1000)	240
Quartz-feldspar schist and leptite; interbedded with quartz-feldspar-mica schist in upper part	840* (740;940)	255
Hornblende schist	280* (410;140)	85
Leptite and quartz-feldspar schist	200* (180;220)	60
Honey Formation		
Hornblende schist; trace marble and quartz schist	690	210
Graphite schist; trace marble, hornblende schist, mica schist, and leptite	290	90
Marble; parts very tremolitic	430	130
Muscovite-quartz schist; trace metaquartzite	1450	440
Marble	75* (5;145)	25
Muscovite-quartz schist; cordierite porphyroblasts in upper part	680	205
Graphite schist; trace marble; leptite unit at base	950	290
Biotite schist	630	190

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*Average of two measurements.

	Thickness	
	ft	m
Graphite schist, marble, and hornblende schist	540	165
Marble and hornblende schist	190	60
Leptite; trace hornblende schist	170	50
Hornblende schist, marble, and diopside rock	500	170
Leptite, quartz-biotite gneiss, and hornblende schist	590	180
Valley Spring Gneiss		
Unit C - Quartz-feldspar gneiss and leptite pink; augen layer near top	180	60
Unit B - Hornblende gneiss, gray (base not reached in this section)	170	50

Note: In Sandy Creek the upper part of the Honey Formation is very different from that in the type section and is given below:

Hornblende schist; some marble, tremolite, schist, quartz-muscovite schists, and leptite	1230	375
Graphite schist; trace marble and leptite	1330	405
Marble	240	75
Graphite schist and graphite-hornblende schist; trace marble and leptite (base not exposed)	740	225