RICE UNIVERSITY

ANALYSIS OF FORELAND BASEMENT DEFORMATION ASSOCIATED WITH THE CLARK MOUNTAIN THRUST COMPLEX, SOUTHEASTERN CALIFORNIA

by

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ABSTRACT

Analysis of Foreland Basement Deformation Associated with the Clark Mountain Thrust Complex, Southeastern California

by Eric Nelson

In the Sevier orogenic foreland exposed in the Clark Mountains of southeastern California, results of this study indicate that Precambrian igneous and metamorphic basement, autochthonous relative to eastward vergent Mesozoic thrusting, exhibits two different modes of post-Precambrian foreland deformation in two separate structures. In the Mesquite Mountains antiform, draping of sedimentary cover (which consists of three thrust sheets overlying thin, autochthonous sediments) has resulted from rigid rotation of basement blocks which core the antiform. This antiform, which probably formed after latest Sevier thrusting, is analogous to Larimide basement uplifts and associated drape structures studied by Stearns (1970) in the Rocky Mountains. Basement in the complex, overturned Kokoweef syncline probably deformed through a combination of spaced (simple) shear and pervasive (pure) shear in response to folding of sedimentary cover associated with early thrusting in the Sevier orogen.

In both structures the unconformable contact between basement and cover is unsheared. Also all foliations and folds in the basement were formed in the Precambrian, and have not been folded during Late Mesozoic-Cenozoic formation of the Mesquite Mountains antiform or the Kokoweef syncline. However basement is more strained on a microscopic scale in the Kokoweef syncline than in the Mesquite Mountains antiform.

Basement, during folding of its sedimentary cover, can adjust in
three possible ways: 1) by folding, 2) by rigid rotation, or 3) by spaced or pervasive shearing. Detailed mapping of foliations presented in this study shows that the basement was not folded during formation of either structure. The unsheared basement-cover contact in the Mesquite Mountains antiform is planar indicating that rigid rotation of the basement occurred, which requires little or no basement shortening. In the Kokoweef syncline, this same contact is folded, which probably requires extensive basement shortening. Thus basement in the Kokoweef syncline adjusted by shearing along reactivated old foliation planes, although the exact mechanism is unclear and enigmatic.

The ultimate cause of foreland basement deformation is dependent on local boundary conditions and not necessarily indicative of regional stresses. Involvement of basement in foreland structures, and the style of this involvement, is controlled by a number of factors including mechanical properties of basement and cover, position and timing of foreland deformation relative to tectonic elements, and scale, all being interrelated. Differences in these factors might explain the lack of pervasively developed basement uplifts in the southern Cordillera relative to the Rocky Mountain foreland.
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1.

INTRODUCTION

Purpose of Study

The purposes of this study are to: 1) determine the geometry and structural development of two basement structures involved in the Sevier orogenic foreland of southeastern California, 2) compare these structures with known examples of foreland basement deformation, particularly the Rocky Mountains, 3) relate basement and cover behavior to a mechanical basis, and 4) speculate on the origin of these two structures in the Rocky Mountain foreland incorporated with knowledge of the tectonic history of the Cordilleran orogenic belt.

Background

Study of the Sevier orogenic belt has been concentrated first and mainly on deformation of fold and thrust belts of the internal portion of the orogen. The reasons are obvious. Because thrusting in geosynclinal areas is often stratigraphically controlled, pre-orogenic sedimentary sequences are easily correlated making palinspastic and paleogeographic reconstructions relatively simple. However, less attention has been given to foreland basement deformation. One possible reason, as Lowell (1974, p. 276) pointed out, is that "observable foreland basement deformation is rare among most of the world's orogenic belts."

The Wyoming Province (Prucha and others, 1965) in the Rocky Mountain foreland was one of the first foreland areas to be studied extensively by structural geologists. This area exhibits a unique style of deformation which consists of sedimentary cover draped over uplifted basement blocks.
Interpretations of these structures have been varied and controversial and have resulted in several different geometric models (Osterwald, 1961; Berg, 1962; Bally, 1975; Burchfiel and Davis, 1975; Woodward, 1976). Stearns (1971, 1975) has recently studied and described features of these structures in detail.

Prucha and others (1965) state that the structural style of the Wyoming Province "is sufficiently distinct to merit consideration apart from that of other terranes of the North American Cordillera." This report describes two structures involving autochthonous basement outside of the Wyoming Province in the Sevier orogenic foreland of southeastern California. The two structures occur within 20 kilometers of each other along the frontal portion of the Clark Mountain thrust belt (Fig. 2). One of these structures, the Mesquite Mountains antiform, is in many ways analogous to drape folds in the Wyoming Province. Basement is involved in the second structure, the Kokoweef syncline, but in a different deformational mode.

Location and Field Work

Both areas are easily accessible on dirt roads (Fig. 1). The Keany Pass area, which includes the Mesquite Mountains antiform, is about 15 kilometers west of Stateline, Nevada along Powerline Road. Detailed geologic mapping of an area approximately 27 square kilometers was done on a portion of the U.S. Geological Survey 15 minute Clark Mountain quadrangle enlarged to a scale of approximately 1:20,570 (Plate 1).

The New Trail Canyon area, in which the nose of the Kokoweef syncline is exposed, is reached by a dirt road in New Trail Canyon approximately 7.5 kilometers west from the paved Morningstar Mine Road in Ivanpah Valley.
Figure 1. Index map. Study area A is Keany Pass area. Study area B is New Trail Canyon area.
Figure 2. Structural index map of the Clark Mountain thrust complex (after Burchfiel and Davis, 1971). Vertical lined pattern = Winters Pass plate; dotted pattern = Mesquite Pass plate; horizontal lined pattern = Keystone plate.
Detailed geologic mapping of an area less than a square kilometer was done on a portion of the U.S. Geological Survey Ivanpah Mountains quadrangle enlarged to a scale of approximately 1:4,561 (Fig. 20).

Field work was done over a period of four weeks in June of 1975. Mapping in both areas consisted of structural analysis of the Precambrian basement rocks, detailed study of the basement-cover contact, and determination of fold geometry exhibited by basal units of the sedimentary cover. This was done to determine the relationship of structures in the basement to structures in the cover. Aerial photographs were used in both areas to assist in the location of data, and for interpretive purposes. Approximately 90 thin sections of both basement and cover rocks were studied to determine relationships between Precambrian structural features and structural features associated with Mesozoic-Cenozoic (?) folding.

Previous Work

D. F. Hewett originally mapped a very large area in the 1920's which includes the area of the Clark Mountain thrust complex. His work, done on a reconnaissance scale, was published in 1956 as U.S. Geological Survey Professional Paper 275. Parts of the Keany Pass area have since been mapped by Clary (1967) and Dobbs (1961). Burchfiel and Davis (1971 and in prep.) have mapped the allochthonous rocks of the Clark Mountain thrust complex in great detail and made regional interpretations. Little work has been published on autochthonous rocks in this region.

In the Wyoming Province several contributions significant to this study were made by Prucha and others (1965), who documented several examples of basement involvement there, and by Stearns (1970), who studied drape structures in the Wyoming Province in detail and discussed the
mechanical basis for the diverse structural styles of deformation during their formation.
Regional Geology of Cordilleran Orogenic Belt

The Clark Mountain thrust complex was named by Burchfiel and Davis (1971) for the southernmost belt of Mesozoic to Early Tertiary (?) thrust faulting and folding in the Cordilleran foreland of southeastern California. The Cordilleran foreland belt can be followed more or less continuously for 2,730 kilometers (1700 miles) from Canada to California and coincides approximately with the eastern margin of the Paleozoic geosyncline in most of the western United States and Canada. This margin formed a pre-thrusting hinge zone which separated a more rapidly subsiding western area from a stable eastern block during most of Paleozoic and Mesozoic time. As a consequence of thrusting across this hinge zone, thick sedimentary sequences of miogeoclinal facies have been thrust eastwards over thinner sedimentary sequences of platform facies.

The frontal thrust belt is typically composed of two to five major thrust faults and a variable number of minor thrusts distributed across a terrain 90 to 130 kilometers wide. Major thrust faults extend up to 160 to 400 kilometers along strike before terminating in folds or tear faults. Almost all of the thrusts dip gently to the west and Bally and others (1966) demonstrated in the Canadian cordillera that some thrust surfaces dip westward for at least 160 kilometers.

Few estimates of cumulative displacements across the frontal thrust belt have been made. In the southern Canadian Rockies North and Henderson (1954) and Shaw (1963) estimated a cumulative figure of 160 kilometers. In the Spring Mountains, Nevada, 40 kilometers north of the Clark Mountain complex, estimates range from 29 to 71 kilometers (Fleck, 1970;
Burchfiel and Davis, in prep.). However, no estimates have been made for the Clark Mountain thrust belt.

Generally, the more westerly thrust plates carry older (and deeper) stratigraphic units. Studies in the Canadian Rockies (Bally and others, 1966, p. 369-371) and in the Idaho-Wyoming thrust belt (Armstrong and Oriel, 1965, p. 1860-1861) indicate that in these areas thrusting progressed from west to east in time (Mesozoic to Eocene or Eocene-Oligocene). Timing of thrusting along the length of the belt is also diachronous.

Regional Geology of Clark Mountain Thrust Complex

The Clark Mountain area exhibits a structural style unlike the eastern part of the Cordilleran thrust and fold belt farther north from Nevada into Canada (Burchfiel and Davis, in prep.). The following features make this area different from areas farther north: 1) involvement of Precambrian crystalline rocks in thrusting, 2) parautochthonous deformation of platform rocks, 3) superposition of early, middle and late Mesozoic deformational events, and 4) presence of extensive Mesozoic igneous activity.

Mesozoic thrusts in Nevada and northwards are stratigraphically controlled. They trend parallel to northeast-southwest paleogeographic and isopach boundaries and are probably decollement thrusts which flatten at depth and may ultimately pass westward into zones of basement involvement and crustal shortening. However in the Clark Mountain complex, thrusts depart from the Paleozoic terrane where they exhibit the features listed above (Burchfiel and Davis, 1972). Burchfiel and Davis (1975) attribute this anomalous behavior to truncation of northeast Paleozoic geoclinal trends by a northwest trending Mesozoic Andean-type plutonic-
volcanic arc (Sierran arc). During this time (early to late Mesozoic) the Cordilleran orogen became structurally two-sided (Burchfiel and Davis, 1968) with east-directed thrust faulting on the east side of the magmatic arc occurring synchronously with oceanic underthrusting of the continental plate to the west of the arc. As the Mesozoic arc and the eastern thrust belt cross the southeastern California, the style of thrusting in this area was controlled by a thermally-induced zone of high ductility caused by the proximity of the magmatic arc (Burchfiel and Davis, 1975).

A brief summary of the geologic history of the Cordilleran orogenic belt in southeastern California is as follows:

1. At least one Late Precambrian rifting event formed a passive continental margin along which Late Precambrian to Cambrian strata were deposited as a westward thickening clastic wedge across the rifted margin.

2. Thick Paleozoic to Lower Mesozoic (?) shelf (miogeoclinal) deposits, mainly carbonates, were deposited to the west while thinner Paleozoic to Jurassic platform deposits were being deposited to the east.

3. Early to Late Mesozoic—Cenozoic (?) thrust faulting juxtaposed western miogeoclinal facies rocks over eastern miogeoclinal and platform facies rocks. Mesozoic plutonism and volcanism occurred throughout this period of thrusting.

4. Tertiary extension caused development of the Basin and Range Province.

5. Quaternary (?) oroclinal bending caused strike-slip faulting and offset of the orogenic belt.
Figure 3. Simplified cross section and reconstruction of the Clark Mountain thrust complex along Powerline Road. pCp = Precambrian gneiss; pCp = Late Precambrian clastics; Pc = Paleozoic carbonates; Cc = autochthonous Cambrian clastics; M = Mesozoic autochthonous rocks.
Burchfiel and Davis (1971, and in prep.) recognized and named the Mesquite Mountains antiform in the northern Clark Mountains and southern Mesquite Mountains. An area of approximately 27 kilometers which exposes the crystalline core of this antiform in the northern Clark Mountains was mapped in detail for this study (Fig. 1, Plate 1).

The Keany Pass area (Plate 1) contains three structural units of Mesozoic age. From lowest to highest these are: 1) autochthon and paraautochthon, 2) Keystone thrust plate, and 3) Mesquite Pass thrust plate (Fig. 3). The structurally higher Winters Pass thrust plate, which is also involved in the Mesquite Mountains antiform, is exposed northwest of the area in the northern Mesquite Mountains. The autochthon of the Clark Mountain thrust complex in this area consists of 1) Precambrian crystalline rocks and 2) lower Cambrian sedimentary rocks which are the basal part of the platform sequence unconformably overlying Precambrian metamorphic rocks. Some of the Cambrian rocks thrust are paraautochthonous below the Keystone thrust plate. In the Keany Pass area the thrust faults have moved Precambrian basement and Late Precambrian and Paleozoic geosynclinal rocks over autochthonous cratonic crystalline and sedimentary rocks. Movement of the thrust plates was in general from west to east relative to the underlying rocks (Burchfiel and Davis, 1971, and in prep).

Autochthonous and Paraautochthonous Rocks

The autochthon of the Clark Mountain thrust complex consists of Precambrian crystalline basement rocks and the basal part of its sedimentary cover. That the term "basement" must be used with care is
exemplified well in this area. Originally, the eroded Precambrian crystalline rocks acted as sedimentary basement for Paleozoic sedimentary rocks. Later, during the Sevier orogeny, the Precambrian crystalline rocks and a small portion of the lower Paleozoic sedimentary cover acted as structural basement (autochthonous rocks) over which the Keystone thrust plate moved. After this thrusting event the same crystalline rocks and probably a small amount of sedimentary cover acted differently as structural basement during formation of the Mesquite Mountains antiform. At this time the allochthonous sedimentary cover acted as structural cover. This relationship will be discussed in the section on structure.

Precambrian Crystalline Rocks

A variety of gneisses and schists, and various igneous bodies crop out in the autochthon of the Clark Mountain thrust complex. These rocks were originally described by Hewett (1956, p. 21) and later by Olson and others (1954) and Dobbs (1961). For the purposes of this study foliation trends and major lithologic boundaries were mapped in order to determine 1) the extent to which post-Precambrian structures have affected the crystalline basement and 2) what controls, if any, foliations had on formation of the Mesquite Mountains antiform. For this reason the many varied granitic and gneissic lithologies are grouped into three divisions: 1) amphibolite gneiss, 2) biotite gneiss and schist, and 3) pegmatite and granitic gneiss. All three main rock types are extensively interlayered.

Amphibolite Gneiss. The amphibolite gneiss consists of dark-gray to black, fine- to coarse-grained, generally fresh amphibolite gneiss. Amphibolite mineralogy consists of 45 to 50 percent idioblastic, inclusion-filled, green amphibole, 30 to 35 percent partially sericitized plagioclase,
and 15 to 20 percent quartz. Minor sphene and rare garnet is present in some thin sections. Biotite occurs in a few samples growing at the expense of amphibole. Textures range from nearly granoblastic to well-foliated. Foliation is formed by alternating 1- to 5-mm thick dark amphibole-plagioclase bands and light plagioclase-quartz bands.

Two large bands of amphibolite gneiss cross the area of basement outcrop (Plate 1). Thinner bands of amphibolite, from .5 to 10 meters thick, also occur throughout the area interlayered with biotite gneiss, granitic gneiss, and pegmatite gneiss (Fig. 10). These bands are all discontinuous and pinch out along strike.

Because amphibolite gneisses are interlayered with high grade biotite-sillimanite gneisses (see below) they were metamorphosed under high grade regional metamorphic conditions.

**Biotite Gneiss and Schist.** Biotite gneiss and schist, which makes up most of the Precambrian exposure, consists of interlayered biotite gneisses and rare schists which include 1) light- to dark-gray biotite gneiss, biotite-garnet gneiss, and biotite-garnet-sillimanite gneiss, 2) dark-brown biotite-hornblende gneiss, and 3) pinkish-brown potassium feldspar augen gneiss. Ranges of principal mineral abundances are given below:

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<tr>
<td>quartz</td>
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<tr>
<td>potassium feldspar</td>
<td>20-50</td>
</tr>
<tr>
<td>plagioclase</td>
<td>0-20</td>
</tr>
<tr>
<td>biotite</td>
<td>5-25</td>
</tr>
<tr>
<td>garnet</td>
<td>5-10</td>
</tr>
<tr>
<td>sillimanite</td>
<td>0-3</td>
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Quartz is usually undulatory or recrystallized.

Feldspars include, in order of decreasing abundance, orthoclase,
microcline, and plagioclase, all of which are partially sericitized. Brown to reddish-brown pleochroic biotite is always present and sometimes partially altered to chlorite or muscovite. Xenoblastic to subidioblastic garnet poikiloblasts form up to 1 centimeter in diameter and are generally post-kinematic. Sillimanite is present both as coarse fibrolite and as larger idioblastic grains associated with biotite.

Texturally these gneisses are fine to medium grained and well foliated. In biotite gneisses foliation is marked by alternating quartz-feldspar bands and biotite-rich bands, and in augen gneisses it is marked by flattened potassium feldspar porphyroclasts (Fig. 4). The foliation often includes folded and boudinaged pegmatite dikes. Garnet-sillimanite bands (up to 1 cm thick) are also folded and sometimes sheared, indicating some deformation followed the peak of metamorphism.

Principal mineral assemblages observed are as follows:

- quartz-plagioclase-potassium feldspar-biotite
- quartz-potassium feldspar-biotite-garnet
- quartz-potassium feldspar-biotite-garnet-sillimanite

The presence of sillimanite with garnet and the lack of muscovite indicates that these pelitic gneisses were metamorphosed under conditions of high grade regional metamorphism (Winkler, 1974, p. 239). The presence of almandine in place of cordierite (the reaction being predominantly pressure dependent) also indicates high grade (temperature) conditions were accompanied by relatively high pressures (Winkler, 1974, p. 89). Experimental data on the two equations indicating the beginning of high grade metamorphism

\[
\text{Qtz} + \text{Musc} = \text{K-spar} + \text{Al}_2\text{SiO}_5
\]

and

\[
\text{Ab} + \text{Or} + \text{Qtz} + \text{H}_2\text{O} = \text{melt},
\]
Figure 4. Precambrian potassium feldspar augen gneiss.
along with the possible reaction
\[ \text{Staur} + \text{Musc} + \text{Qtz} = \text{Al}_2\text{SiO}_5 + \text{Garnet} + \text{Biot} + \text{H}_2\text{O} \]
indicate P,T conditions of 5 to 6 kilobars at 650° to 700°C. (Winkler, 1974, p. 217). Occasional alteration of biotite to chlorite indicates local retrograde reactions, probably as a result of intrusion of post-tectonic pegmatites.

**Pegmatite and Granitic Gneiss.** As mentioned above, many bodies of pegmatite and granitic material have intruded the other Precambrian rocks. These bodies range in size from 2-cm thick pegmatite dikes to larger irregular pegmatite and granitic intrusions, all of which range from pre-tectonic (foliated) to post-tectonic (non-foliated). Coarse- to very coarse-grained, white pegmatite consists of 60 to 80 percent potassium feldspar (mostly microcline and perthite), 20 to 35 percent quartz, and minor biotite, garnet, and sillimanite. Riebeckite and muscovite crystals up to 5 cm in longest dimension are present locally. Fine- to medium-grained, white, pink, and light-gray granitic gneisses have similar quartz and feldspar abundances with up to 5 percent biotite. Biotite is partially altered to chlorite or muscovite. Foliation is defined by oriented biotite grains, and in some samples by flattened quartz and feldspar.

These felsic gneisses crop out in small irregular bodies, for example on top of Keany Peak (VABM 5419), and also interlayered with biotite and amphibolite gneisses. These two modes of occurrence provide a relative chronology of multiple or progressive deformation and metamorphism. Felsic gneisses interlayered with high grade gneisses contain garnet and sillimanite which grew as late-interkinematic or post-kinematic porphyroblasts. The irregular bodies of granitic gneiss contain muscovite and no sillimanite and are probably associated with retrograde metamorphism in the surrounding biotite gneisses. Thus at least two periods of
17.

intrusion of granitic material are indicated. Relationships between intru-
trusion, deformation and metamorphism are shown schematically in Figure 5.

Sedimentary Cover

Autochthonous sedimentary rocks exposed in the Keany Pass area con-
sist of a thin, terrigenous, platform sequence which underlies the Key-
stone thrust plate. East of Mesquite Pass, younger brecciated paraautoch-
thonous rocks are present above the terrigenous sequence and below the
Keystone basal thrust fault.

Tapeats Sandstone. Tapeats Sandstone, originally described by
Noble (1914, p. 100) in the Grand Canyon area, was recognized in the
Mesquite Pass area by Hewett (1956). Burchfiel and Davis (in prep.) cor-
related exposures of Tapeats Sandstone and overlying Bright Angel Shale
on the west side of the Mesquite Mountains antiform with similar rocks
on the east side of the antiform, which had previously been mapped as
Permian Kaibab Limestone (Hewett, 1956) and Triassic Moenkopi Formation
(Clary, 1967).

In this area the Tapeats Sandstone exhibits two modes of occurrence.
Along the west side of the Mesquite Mountains antiform approximately 85
meters of pale-red to purple, medium- to very coarse-grained quartzitic
sandstone is in depositional contact with Precambrian crystalline rocks
(Plate 1). Poorly- to well-rounded quartz grains make up over 95 percent
of the rock, the rest being chert fragments, feldspar, and magnetite.
Primary structures include cross-bedding, possible graded bedding, and
bottom markings and worm tubes in the upper part.

The basal depositional contact is often marked by pebble to cobble
conglomerates and locally by breccias of weathered basement. In a few
places a diabase sill intrudes the lower contact. The upper contact is
Figure 5. Schematic relationship between deformation, metamorphism, and intrusion in Precambrian basement of the Clark Mountains area.
gradational into the Bright Angel Shale with shale beds increasing in amount upward relative to sandstone beds. Along the west limb and in the nose of the Mesquite Mountains antiform a light gray rhyolite sill intrudes the upper contact.

Little evidence of deformation is present in the Tapeats Sandstone along the west limb and in the nose of the Mesquite Mountains antiform. A few small scale folds occur, probably associated with thrusting. Minor slickensides are present on fracture planes near the basal contact and might indicate some adjustment during formation of the Mesquite Mountains antiform. Microscopically some quartzitic sandstones show undulatory extinction, grain boundary recrystallization, and local shearing (Fig. 6). In one location (N 1/2 N 1/2 sec. 32, T. 17 1/2N., R. 13E.) a weak foliation of slightly elongate quartz grains and secondary muscovite was found parallel to bedding. However, at the same location (as along most of the west limb) no surfaces of slip are present at the Tapeats-gneiss contact (Fig. 8).

At one locality (NW 1/4 NW 1/2 sec. 1. T. 17N., R. 13E.) on the northeast side of the Mesquite Mountains antiform the Tapeats was found undeformed and in depositional contact with weathered basement. However, along this side of the antiform the Tapeats is usually exposed as a vertical band of quartzite, 10 to 15 meters wide, which runs discontinuously for about 6 kilometers along the Ivanpah fault. Here the Tapeats is a white to light tan, rust-weathering, highly indurated metaquartzite (Fig. 7). Bedding and other primary features are absent. These highly resistant outcrops of metaquartzite have a coarsely porous "honeycomb" structure characteristic of shattered rocks in desert areas of the southwest. Because of this deformation, the lower contact of the Tapeats in this area is here considered a minor(?) splay of the Ivanpah fault. The upper
Figure 6. Local deformation in Tapeats Sandstone on west limb of Mesquite Mountains antiform. Quartz grain shows kink bands (vertical), deformation lamellae (horiz.), and recrystallization along microfault and grain boundaries. (Mag 16X).

Figure 7. Brecciated and sheared Tapeats Sandstone along east limb of Mesquite Mountains antiform. (Mag. 4X, plain light).
Figure 8a. Unsheared depositional contact between conglomeratic basal Tapeats Sandstone and Precambrian crystalline basement.

Figure 8b. Photomicrograph of contact (a-a'). $S_0$ = bedding defined by cross-bedded magnetite bands.
contact with the Bright Angel Shale and occasionally Goodsprings Dolomite is also commonly faulted.

Although no fossils have been found in the Tapeats Sandstone in the Clark Mountain area, Burchfiel and Davis (in prep.) have assigned it an Early Cambrian age based on correlations with areas to the north (Hewett, 1956; Longwell and others, 1965) and to the south (Hazzard, 1954).

**Bright Angel Shale.** Overlying the Tapeats Sandstone are 50 to 80 meters of reddish-brown and green shales interbedded with grey limestone and orange-weathering silty limestone of the Bright Angel Shale. The lower contact is gradational with the Tapeats and the upper contact is always faulted, either by the Ivanpah fault, by the Keystone thrust, or by parautochthonous thrusts below the Keystone plate. Autochthonous Bright Angel Shale along the west side of the Mesquite Mountains antiform is generally undeformed except for minor faulting and folding probably associated with parautochthonous deformation. However, deformation of the Bright Angel Shale along the east side of the antiform is probably associated with movement on both the Keystone and Ivanpah faults.

The Bright Angel Shale is assigned an Early and Middle Cambrian age based on correlations made by Dunne (1972, p. 22) and by Burchfiel and Davis (in prep.).

**Paraautochthonous Rocks**

In the Kean Pass area rocks considered paraautochthonous by Burchfiel and Davis (1971) are present below the Keystone thrust just east of Mesquite Pass (Plate 1, W 1/2 secs. 20 and 29, E 1/2 secs. 19 and 30, T. 17 1/2N., R. 13E.). These rocks consist of brecciated and sliced up Bright Angel Shale and Goodsprings Dolomite of the platform sequence. They were disrupted as a result of thrusting of the overlying major thrust
sheets containing geosynclinal sequence rocks.

Allochthonous Rocks

Because Burchfiel and Davis (1971, and in prep.) have described the allochthonous sequence of the Clark Mountain thrust complex in detail, only minor description of features pertinent to this study will be made.

Keystone Thrust Plate

The Keystone thrust fault was named by Hewett (1931) in the Goodsprings district 19 kilometers northeast of the map area. It has been correlated for 240 kilometers along its trace by Hewett (1931) and Longwell and others (1965), and Burchfiel and Davis (1971) have correlated the Keystone thrust with the basal thrust in the Clark Mountain complex, thus extending it even farther. Hewett (1956) first mapped the Keystone thrust in the Clark Mountains as the Clark Mountain fault and thought it was a high angle normal fault. The Keystone thrust plate is between the Keystone and Mesquite Pass basal thrusts (Fig. 3) and is the only plate in the Clark Mountain complex that carries rocks younger than Early Devonian (?) (Burchfiel and Davis, in prep.). These rocks include a thick section of Lower to Upper Paleozoic mainly carbonate rocks (Fig. 9) which have been interpreted as being transitional between platform and Cordilleran miogeocline sequences (Burchfiel and Davis, 1971).

The Keystone thrust fault is predominantly stratigraphically controlled. Rocks in the Keystone plate thin southward from Mesquite Pass, where they are approximately 1370 meters (4500 feet) thick, to the Mescal Range where they are cut out by the next higher thrust fault. Displacement on the Keystone thrust took place between 135 m.y. ago and 95 m.y. ago based on ages of plutonic rocks which are involved in and which cut the thrust
Figure 9. Comparison of stratigraphic sections between Mesquite Mountains antiform and Rattlesnake Mountain structure in Wyoming.
fault respectively (Sutter, 1968).

Mesquite Pass Thrust Plate

The Mesquite Pass thrust plate is the second major thrust plate in the Clark Mountain complex. The Mesquite Pass thrust fault was originally mapped by Hewett (1956) as the Mesquite thrust and later remapped and correlated with thrusts in the Las Vegas area by Burchfiel and Davis (in prep.). In the Mesquite Pass area the plate is approximately 1300 meters (4650 feet) thick (Fig. 9) and consists of three major slices. The basal thrust is not stratigraphically controlled and carries Precambrian crystalline basement, Late Precambrian clastics, and Cambrian and Devonian (?) carbonates (Fig. 9).

The earliest movement of the Mesquite Pass plate occurred prior to 200 m.y. ago as plutons of this age cut the basal thrust, and the latest movement was probably early Late Cretaceous (Sutter, 1968).

Winters Pass Thrust Plate

The Winters Pass thrust plate is the third and highest plate in the Clark Mountain complex. Although not exposed in the Keany Pass area, it was probably involved in folding of the Mesquite Mountains antiform. The Winters Pass plate contains several thousand feet of Precambrian crystalline rocks at its base. At least 3050 meters (10,000 feet) of Late Precambrian carbonates and clastics and Cambrian and Devonian (?) carbonates are present above the crystalline rocks (Fig. 9).

The Winters Pass thrust fault is characterized by a wide zone of cataclastically deformed crystalline rocks at the base of the thrust plate. This deformation occurred at depth during early movement of the thrust plate prior to 200 m.y. ago, and movements in the Late Mesozoic
carried these mylonites to a shallow level (Burchfiel and Davis, in prep.).

Structure

The structural evolution of the Keany Pass area can be divided into three main events: 1) Precambrian deformation and metamorphism, 2) Mesozoic thrusting and folding, and 3) Mesozoic or Cenozoic post(?)-thrusting high-angle faulting and associated drape folding. The Mesozoic structures have been described in detail by Burchfiel and Davis (in prep.) and were briefly reviewed in the previous section.

Precambrian Structure and Metamorphism

Precambrian crystalline rocks in the Keany Pass area have undergone a complex history of multiple deformation and regional metamorphism. Over most of the area Precambrian gneisses are well foliated, although granitic and pegmatite gneisses can range from non-foliated to well-foliated. Most of the Precambrian gneisses that core the Mesquite Mountains antiform are interlayered on both a large and small scale. Mesoscopically this banding or interlayering can be seen to include isoclinal folds and transposed compositional layering (Fig. 10a). Macroscopically, proof of large scale transposition is more difficult. In many places bands of amphibolite (up to 100 meters thick) interfinger with white pegmatite or granitic gneiss (Fig. 10b). Whether this relationship was caused by large scale isoclinal folding and transposition or by lit-par-lit injection followed by flattening or shearing is difficult to determine because of inadequate exposure and intrusion of later igneous bodies.

In the western part of Plate 1 the percentage of non- or less-foliated pegmatite and granitic material is high. The rocks in this
Figure 10a. Mesoscopic interlayering of amphibolite gneiss and felsic gneiss.

Figure 10b. Macroscopic interlayering of amphibolite gneiss and felsic gneiss.
area have been labeled Precambrian pegmatite and granite gneiss (pCp) on Plate 1 but include some amphibolite and biotite gneisses characteristic of the rest of the Precambrian basement. Intrusion of "granitic" material was pre-, syn-, and post-kinematic with respect to more than one phase of deformation. This is indicated by non-foliated pegmatite that intrudes folded foliation in granitic gneiss. The eastern limb of this fold is cut by a fault of unknown extent or displacement which might be related to Mesozoic(?) - Cenozoic formation of the Mesquite Mountains antiform (see below).

At least two and possibly four phases of deformation have affected the Precambrian basement. Paragneiss protoliths were probably pelitic or arkosic sediments layered with basaltic flows or intrusions (sills?) based on the silicic composition of many of the banded gneisses interlayered with amphibolite. The first recognizable deformation \( (F_1) \) is characterized by isoclinally folded pegmatite veins, and foliation \( (S_1) \) in banded gneiss and granitic gneiss (Fig. 11). However because many of these structures fold a pre-existing foliation, an earlier deformation \( (F_1') \) is inferred. A second phase of deformation \( (F_2) \) is evidenced by re-folding of these \( F_2 \) isoclinal folds on a mesoscopic scale. Most of these folds have a similar-type geometry which is compatible with ductile deformation at amphibolite grade. Although few examples of a second foliation \( (S_2) \) are present, probable intersection lineations occur throughout the area.

Two megascopic structures fold foliations in the Keany Pass area: 1) a fold within granitic gneisses in the southwest part of the area (discussed above) and 2) a large kink across two amphibolite bands (Plate 1, near VABM 5419). The two structures are orthogonal and probably occurred during different folding events. That these folds possibly occurred after
Figure 11. Isoclinally folded pegmatite vein in Precambrian gneiss.
the mescopic folding event ($F_3$) is evidenced by some scatter of $F_2$ and $F_3$ minor fold and mineral lineations (Fig. 12).

Lanphere (1964) has dated metamorphism in similar gneisses in the Mountain Pass area (Fig. 1) as occurring 1.65 billion years ago.

There are two lines of evidence showing that structures in the crystalline basement are Precambrian and not associated with formation of the Mesquite Mountains antiform (or, for that matter, with Mesozoic thrusting). First, none of the small scale structures of the basement are found in the sedimentary cover. This can be seen on Plate 1 where the large kink band near VABM 5419 is truncated at and does not fold the contact with the Tapeats Sandstone to the east. Secondly, the crystalline basement is not folded on the large scale of the Mesquite Mountains antiform.

Mesquite Mountains Antiform

The Mesquite Mountains antiform (and associated Ivanpah fault) is interpreted here as a drape fold analogous to similar structures described in the Wyoming Province by Prucha and others (1965) and Stearns (1970). A brief discussion of the mechanical basis for different structural styles between basement and cover in drape structures is followed by a description of the features of the Mesquite Mountains antiform. The Mesquite Mountains antiform is then compared to a well-studied drape fold in Wyoming. Finally the possible mechanisms of formation of the Mesquite Mountains antiform are discussed.

The term basement has numerous meanings. In discussing the formation of drape folds associated with basement uplifts, Stearns (1970) has defined basement essentially on a mechanical basis as follows:

"Basement includes those rocks which are Statistically homogeneous and isotropic, which behave in a brittle manner to depths of at least
Figure 12. Lineation data for Precambrian metamorphic rocks in the Keany Pass area. Lower hemisphere equal area plots.
50,000 feet, and below which layered rocks do not occur. Although in this definition there is no implication of either age or lithology, Precambrian crystalline granitic rocks comprise most of the basement in the Wyoming Province. Excluded are foliated or layered rocks of any age."

Because it is foliated and layered, Precambrian basement in the Clark Mountain complex does not exactly conform to this definition. The effects of this difference are discussed below.

Borg and Handin (1966) found that experimentally deformed basement rocks behave brittlely under temperatures (500 degrees C) and pressures (5 kilobars) simulating depths of up to 75,000 feet (46,600 meters). Although these experiments were done at high strain rates, Heard (1962) used much slower strain rates under the same conditions and found no appreciable increase in ductility. The behavior of sedimentary rocks is in contrast to that of the basement. Experimental deformation of sedimentary rocks (Handin and Hager, 1957; Handin and others, 1963; Handin, 1966) shows that, except under simulated near-surface conditions, most sedimentary rocks are much more ductile than basement rocks. Thus experimental data support the contrasting behavior of crystalline basement and layered sedimentary rocks in the upper part of the crust.

These experimental data, along with surface, subsurface and seismic data (Stearns, 1975) show that the basement in the Wyoming Province behaves as a brittle material and deforms by rigid body rotations. Because rigid rotation of basement blocks on planar faults would create a difficult room problem (see Fig. 13), curved faults have been invoked. Hubbert (1951), from sandbox experiments, and Hafner (1951), from theoretical analysis, showed that a single set of boundary conditions can lead simultaneously to potential normal, high-angle reverse, and thrust faults, and all can be curved in cross section. Stearns (1970) has shown that one of
Figure 13. Room problem created by rotation of rigid blocks. (Modified from Stearns, 1970).

Figure 14. Tilting of blocks through movement on distributed shear planes as one solution to room problem. Potential shear surfaces are conjugate to boundary fault between blocks. (After Prucha and others, 1965).
Hafner's boundary value solutions fits the general requisite of Laramide basement deformation in the Rocky Mountain foreland. Prucha and others (1965) also suggested distributed shear along sets of closely spaced parallel fractures as a possible mechanism to avoid the room problem (see Fig. 14). However this has been disproved at Rattlesnake Mountain in Wyoming where numerous pegmatite dikes are not offset in the basement. Stearns, 1970).

The Mesquite Mountains antiform consists of a gentle west limb (analogous to block 1 in Figure 16), and a steep to vertical east limb, which is cut by the Ivanpah fault (Plate 1, Fig. 15). The antiform plunges approximately 24° NW either as a result of scissors movement on the Ivanpah fault or due to tilting after formation of the antiform. The Ivanpah fault does not cut completely through the fold as displacement on it dies out about 2.3 miles (3.7 kilometers) northwest of Mesquite Pass, within the Mesquite Pass thrust plate.

Although not mapped in detail, the Clark Mountains northeast of the Ivanpah fault are probably structurally a synform which plunges northwest under Mesquite Valley. In fact the Mesquite Valley itself appears to be a large synform (B. C. Burchfiel, pers. communication, 1975).

Drape folds associated with basement uplifts in the Rocky Mountain foreland have been recognized by geologists for many years, and varied interpretations concerning their origin have been made. In this region, such basement uplifts are well exhibited in the Wyoming Province. Prucha and others (1965) originally defined the Wyoming Province as that area south of the Canadian border, east of the Montana and Wyoming fold belts, north and east of the Colorado Plateau, and west of the Great Plains. They recognized that the structural style of the Wyoming Province was distinct from other areas of the North American cordillera. Stearns
Figure 15a. Cross section of Mesquite Mountains antiform. Symbols as on Plate 1.
Figure 15b: Cross section of Mesquite Mountains antiform. Symbols as on Plate 1.
Figure 16. Controlled cross section through Rattlesnake Mountain. (From Stearns, 1970).
(1970, 1971) has studied these structures in detail and observed that crystalline basement deforms in a brittle fashion through faulting, whereas overlying sedimentary rocks usually deform in a more ductile fashion by draping over uplifted and rotated basement blocks. The two different styles of deformation have occurred simultaneously in the Wyoming Province. Some mechanical basis is needed to explain the difference in style.

One of the best studied drape folds in the Wyoming Province is at Rattlesnake Mountain, Wyoming (see Fig. 16). This structure exhibits many of the features common to other such structures in the Wyoming Province (Stearns, 1971). As shown on Figure 16 the geometry of the Rattlesnake Mountain structure can be described in terms of distinct blocks (1 through 5), of which blocks 1, 2, and 3 are well developed in most drape folds (Stearns, 1971). Significant features of the Rattlesnake Mountain structure include the following:

1) the basement fault with 7,000 feet (2,133 meters) of throw rapidly dies out in the sedimentary cover
2) the main basement fault causes secondary faults in the sedimentary cover near the surface
3) not all faults that cut the sedimentary cover go into the basement, particularly normal faults
4) no thinning of the sedimentary cover occurs around the drape fold
5) detachment of the sedimentary cover occurs to adjust for draping over basement blocks with no thinning of the cover
6) shale at the bottom of the sedimentary cover acts as a "space-filler" in gaps created during rotation of rigid basement blocks
7) some cataclastic flow occurs on the corners of rotated blocks, but the basement-cover contact is otherwise planar over the entire exposed region.
Dips on the west limb of the Mesquite Mountains antiform ranging from 20 to 50 degrees are steeper than the average 13- to 16-degree maximum dip on basement surfaces (block 1) in the Wyoming Province. However basement surface dips of 22 to 23 degrees occur in the Fort Collins area of the Colorado Front Ranges, and blocks along the Beartooth Mountain front have rotated up to 60 degrees (D. W. Stearns, pers. communication, 1976). The steep dip angle on the west limb could be partially due to an initial tilting of the basement-cover contact prior to rotation during formation of the Mesquite Mountains antiform.

In the Wyoming Province the basement surface is essentially smooth and evenly tilted as evidence by subsurface data and the regularity of basal Cambrian transgressive sandstone (Stearns and others, 1975). Although subsurface data are lacking in southeastern California, it is assumed here that the basement surface in the Mesquite Mountains antiform has a similar geometry because of the general planar attitude of the basal Tapeats Sandstone and overlying structural units.

The eastern limb of the Mesquite Mountains antiform is cut by the Ivanpah fault, which was originally mapped by Hewett (1956) and later by Burchfiel and Davis (1971) in more detail. Where exposed, the fault consists of up to three splays which probably merge at depth. The eastern and main fault, as mapped by Burchfiel and Davis, dips approximately 70° NE and is marked by juxtaposition of rocks of the lower Keystone thrust plate against rocks of the upper Keystone plate and Mesquite Pass plate (Plate 1, Fig. 15). The western splay of the Ivanpah fault is marked by a discontinuous band of brecciated and sheared Tapeats Sandstone and Bright Angel Shale (Plate 1, Fig. 15). This band of deformed rock is probably a sliver of Tapeats Sandstone and basement(?) that has been formed as the main basement fault splays out. Such structures have been
documented in the Wyoming Province (Foose and others, 1973, Fig. 10), and have also been produced in experimentally created drape folds (Stearns and Weinberg, 1975; Fig. 17).

The western splay locally cuts into the basement, and sometimes cuts out the Tapeats Sandstone completely. One explanation for the latter might be depositional discontinuity of the Tapeats, but this line of argument is probably invalid as the Tapeats is continuous elsewhere in the Clark Mountains area. Slicing of small basement blocks where the main fault splays is a better explanation for this feature.

A high angle reverse fault is present between the two major splays of the Ivanpah fault (see Fig. 15, section A-A', and Plate 1, secs. 21, 27, 28, and 34, T. 17 1/2N., R. 13E., and secs. 33 and 34, T. 18N., R. 13E.) and is probably a minor fault formed during draping of the sedimentary cover (see Fig. 18b). It has a small stratigraphic throw, as it often faults Bright Angel Shale against itself. This minor fault was probably not associated with parautochthonous thrusting as it makes a low angle with the Keystone thrust and has the wrong sense of displacement when the Keystone is rotated back to subhorizontal. Dynamically this fault can be explained by local compression caused by flexuring of the sedimentary cover during draping (see Fig. 18b).

In the Colorado Front Ranges drape structures occur within sandstones and shales of the Lions Formation, whereas the 700-foot thick Fountain Sandstone behaves as brittle basement like the crystalline rocks it rests on.* The Tapeats Sandstone also acted as brittle basement as defined above. This is evidenced by the unsheared basal contact. Thus one would

*This area is being studied by Vince Matthews of the University of Northern Colorado; D.W. Stearns, pers. communication, 1976.
Figure 17. Experimentally created drape fold. Basement is block of sandstone with two sandstone layers over it. Cover is limestone layer. Precut basement fault dips 60 degrees. Note how fault splays out in basement near surface. (From Stearns and Weinberg, 1975).
Figure 18. Development of Mesquite Mountains antiform.
(a) initial basement faulting and sediment draping;
(b) splaying of basement fault and development of
small reverse fault on limb of fold; (c) basement
fault cuts higher in sedimentary cover; present con-
figuration (d) new splay of basement fault takes up
most of displacement. See Plate 1 for rock symbols.
expect the Tapeats to maintain a constant strike along the gentle western limb of the antiform (that is, analogous to block 1 in Fig. 16). However, attitudes in the Tapeats begin to swing around in the nose of the fold along with the rest of the overlying sedimentary cover. Two explanations are possible. First, Stearns (1975, p. 150) notes that "the corners of many rotated basement blocks show evidence of cataclastic flow, but the contact is otherwise planar over the entire region." Although it is possible that the Tapeats has folded around smashed basement in the nose of the fold (Mesquite Pass area), no evidence of cataclasis was seen in the basement or the Tapeats in this area. This variation in attitude around the nose can better be explained with rotated blocks of basement bounded by curved splays of the Ivanpah fault (see Fig. 17). As stated above the association of these features with drape folds is well documented in the Wyoming Province, and is also seen in experimentally created drape folds (Stearns and Weinberg, 1975).

Although Prucha and others (1965, p. 983) thought that thinning of the sedimentary cover probably occurs over drape folds, Stearns (1970) has shown that this is not the case for carbonate sections, by accurately measuring stratigraphic sections around drape folds. Two types of adjustment have occurred in the Rattlesnake Mountain structure as a result of this lack of thinning. First, a regional detachment (Heart Mountain detachment) has occurred, usually near the bottom of Ordovician carbonates which overlie basal Cambrian shales. Secondly, Cambrian shales act as a "space-filler" in the voids created as a result of faulting the rigid basement blocks but not the cover (Fig. 16). Due to inadequate exposure and complex structure within the overlying thrust plates, thinning cannot be proven in the Mesquite Mountains antiform. However, as the sedimentary section in the Mesquite Mountains antiform consists mostly of a
thick carbonate sequence (Fig. 9), it probably did not thin. Detachment, as occurs at Rattlesnake Mountain, is also not easily proven in the Mesquite Mountains antiform, although pre-existing detachment surfaces such as the Keystone thrust fault could have been easily reactivated. Also the Bright Angel Shale is in a position exactly analogous to the Cambrian shales at Rattlesnake Mountain (compare Figs. 15 and 16) and could have acted both as a "space-filler" and as a horizon for detachment. Such detachment or pervasive deformation might be indicated by small-scale folds in shales within the Ivanpah fault zone, although these folds could also be due to earlier movement associated with the Keystone thrust or to the Ivanpah fault.

Mechanism of Formation. There are three possible mechanisms by which the basement could have deformed during formation of the Mesquite Mountains antiform. These are: 1) folding of the basement rocks, 2) pervasive or distributed shear in the basement, and 3) rotation of the basement as a rigid block, the east side of which is bounded by the Ivanpah fault. The first possible mechanism can be discarded because detailed mapping shows that the Mesquite Mountains antiform (expressed by the sedimentary cover) does not fold the basement rocks (Plate 1, Fig. 15).

The second possible mechanism, pervasive or distributed shear in the basement, is supported by the observed orientation of the foliation, which is generally steep and subparallel to the axial plane of the antiform and also to the Ivanpah fault. Also, this mechanism can be used to explain the apparent folding of the Precambrian-Cambrian unconformity in the hinge area (mesquite Pass). However, shear fractures spaced, say, 2 to 10 meters apart, probably do not occur in the basement. This is indicated by the continuity of the two amphibolite bands on Plate 1 which show no offset, except on two minor faults perpendicular to the foliation. Also, two
large scale Precambrian folds (Fig. 15) have locally oriented the foliation at a high angle to potential axial slip planes. No evidence is present in the field to indicate adjustment on fractures of close spacing or by cataclastic flow.

As shown above, apparent folding of the Tapeats Sandstone in the hinge area can be explained by more widely spaced faults (splays of the Ivanpah fault). This explanation would involve rotation of rigid blocks and cannot be considered pervasive shear. Similarly, possible cataclastic flow of basement in the hinge would be a local occurrence and thus would not be considered pervasive. Thus, the Precambrian basement neither folded or adjusted by major pervasive slip or major cataclasis during formation of the Mesquite Mountains antiform.

Splaying of the Ivanpah fault and possible local cataclastic flow are actually second order features associated with the third, and I believe most likely, mechanism. That is, rigid rotation of the basement with draping of the sedimentary cover over it. That the crystalline basement acted in a brittle manner (thus facilitating faulting and rotation) is evident from the lack of post-Precambrian structures other than minor faults in the basement.

As discussed earlier, the crystalline basement in the Clark Mountain area does not conform to the definition used by Prucha and others (1965) and Stearns (1970), but it nonetheless acted as homogeneous, isotropic rock due to large scale folding of foliation (Fig. 19). On a smaller (local) scale foliation is parallel to the Ivanpah fault and possibly controlled the orientation of the Ivanpah fault (Fig. 15a). Note, however, that this relationship does not indicate the direction of maximum principal stress causing the uplift.

The actual rotation of the basement block was accomplished by
Figure 19. Cross section showing dependence of mechanical homogeneity on scale. Scale is same as on Plate 1 for A, and Figure 20 for B. In resultant deformation, basement at scale A was mechanically homogeneous and isotropic as opposed to basement at scale B which was mechanically heterogeneous and anisotropic.
relative vertical displacement on the Ivanpah fault. Whether the displacement is considered normal or reverse depends on which way the fault curves at depth. The west side of the Ivanpah fault is relatively up, and some scissors movement has probably occurred as horizontal separation decreases to the northwest until the fault trace finally ends in the Mesquite Mountains. Where the fault trace disappears need not be the actual hinge point of the fault, but could be where the fault ceased to cut the sedimentary section in the drape fold (point x on Figure 18d). That is, the Ivanpah fault may have uniform throw along it, but later tilting has caused its present exposure pattern.

The time of formation of the Mesquite Mountains antiform is uncertain. Certainly it formed after some amount of thrusting of the Clark Mountain thrust complex and probably after completion of thrusting because it cut the lower two thrusts. Burchfiel and Davis (in prep.) suggest that the Mesquite Mountains antiform was formed, and subsequently the Ivanpah fault, as a result of the same horizontal compression which formed the Clark Mountain thrust complex. Two other regional deformations which could have caused the Mesquite Mountains antiform after Mesozoic thrusting are 1) Basin and Range development and 2) strike slip faulting.

The Mesquite Mountains antiform could have formed as a result of Mesozoic-Cenozoic (?) thrusting (horizontal compression), during Basin and Range development (extension), or during formation of the Las Vegas shear zone (wrenching). It can be argued that a vertical uplift like the Mesquite Mountains antiform cannot be formed in any of these three regional stress environments. However in all of these stress environments many secondary local stress systems are set up. Thus, although the net effect of a regional stress environment can be one of compression, extension, or wrenching, many minor local effects (such as vertical uplifts)
can occur. Hafner's (1951) solutions serve well to illustrate this point by showing the numerous fault orientations possible from one set of boundary values.

NEW TRAIL CANYON AREA (Kokoweef Syncline)

The Kokoweef syncline, a large overturned fold within the autochthonous platform sequence below the Keystone basal thrust, was mapped and named by Burchfiel and Davis (in prep.). The syncline is in the Ivanpah Mountains and Mescal Range about 20 kilometers south of the Mesquite Mountains area (Fig. 1). The nose of the syncline, which exposes Precambrian crystalline rocks, was mapped in detail for this study to determine the style of basement involvement in the fold (Fig. 20).

Structurally above autochthonous and paraautochthonous rocks shown on Figure 3 the same allochthonous plates described in the Mesquite Mountains area are present. These are, lowest to highest, the Keystone thrust plate, the Mesquite Pass thrust plate, and a probable equivalent to the Winters Pass thrust plate. The Keystone plate however is cut out in the southern part of the area. East of the autochthonous rocks of the Kokoweef syncline across the Kokoweef fault, only autochthonous Precambrian crystalline rocks are present.

Autochthonous Rocks

As in the Mesquite Mountains antiform, autochthonous rocks in the New Trail Canyon area consist of Precambrian gneiss below sedimentary cover. In this area, the sedimentary cover includes a complete section of the Clark Mountains autochthon including Cambrian to Jurassic rocks. Burchfiel and Davis (in prep.) have described this sequence in detail and
EXPLANATION

Devonian(?)
[ DCg ] Goodsprings Dolomite
Cambrion
[ Bka ] Bright Angel Shale
[ Et ] Tapeats Sandstone
Precambrian
[ pCg ] Precambrian gneiss

UNCONFORMITY

SYMBOLS

30
Strike and dip of bedding

60
Strike and dip of overturned bedding

87
Strike and dip of foliation

Strike and dip of vertical foliation

Contact

High-angle fault; U, unthrown side; D, downthrown side

Thrust fault showing dip; barbs on upper plate

Overturned syncline showing plunge

Precipitated rock

Figure 20. Geologic map of Kokoweef syncline, Ivanpah Mountains, southeastern California.
Figure 21. Cross sections of Kokowee syncline.
only the significant units exposed in the nose of the Kokoweef syncline will be briefly described along with the basement.

Precambrian crystalline rocks can be traced continuously from Mesquite Pass south along the eastern Clark Mountain front to the New Trail Canyon area in the Ivanpah Mountains. Most of the lithologies found in the Mesquite Mountains area also are present at the New Trail Canyon area. These include amphibolite gneiss, biotite-garnet gneiss, biotite-sillimanite-garnet gneiss, pegmatite gneiss and granitic gneiss. Because sillimanite and garnet occur in the rocks there is no evidence to suggest that a major thermal or tectonic boundary exists within the basement between the two areas.

Cambrian Tapeats Sandstone rests unconformably on crystalline basement around the nose of the syncline. Along the eastern limb of the syncline the Tapeats is faulted against basement by the Kokoweef fault (Figs. 20 and 21). In this area the Tapeats consists of a lower and an upper member. The lower unit is reddish-brown, medium- to coarse-grained quartzitic sandstone. The upper unit is a white, well-indurated orthoquartzite (Fig. 22). The lower contact is characterized by basal conglomerate (Fig. 23) and occasional purple weathering zones above similar colored basement. Thickness of the Tapeats in this area ranges up to 180 meters (600 feet) but is difficult to measure accurately in the nose due to complex and overturned minor folding.

The Tapeats Sandstone is overlain by brown and green shale and siltstone of the Bright Angel Shale. The Bright Angel Shale shows minor parasitic folding in the tight hinge of the syncline.

Parautochthonous Rocks

In the map area (Fig. 20), Cambrian and Devonian(?) Goodsprings
Figure 22. Well-indurated (recrystallized?) orthoquartzite of upper unit of Tapeats Sandstone exposed in the Kokoweef syncline. (Mag. 5X, crossed nicols).
Figure 23. Unsheared contact between Precambrian gneiss (right) and vertical basal conglomerate of Tapeats Sandstone on the overturned limb of the Kokoweef syncline.
Dolomite is the only parautochthonous unit exposed. It consists of occasionally brecciated dolomite in a number of imbricated thrust slices. The carbonate rocks are recrystallized due to intrusion of nearby plutonic rocks.

Structure

The Kokoweef syncline is a complex, northwest plunging, eastward overturned fold that can be traced for 6.4 kilometers (4 miles) northwest of the New Trail Canyon area. It is non-cylindrical and characterized by a pronounced variability in form. The eastern limb, which is truncated by the Kokoweef fault, dips 40 to 80 degrees west. The western limb is overturned in the New Trail Canyon area but varies from overturned to upright in exposures to the northwest. The western limb is truncated in this area by a parautochthonous thrust fault below the Keystone basal thrust. This thrust fault dips 30 to 40 degrees west along most of its length, except in the area of Figure 20 where it quickly steepens to 70 degrees. Burchfiel and Davis (in prep.) interpret this steepening as being due to a splay of the Kokoweef fault that projects beneath the thrust fault in this area.

Foliation in the basement generally dip steeply west. Structures in the basement include small scale folding, transposition, and other Precambrian features identical to crystalline basement in the Mesquite Mountains antiform. Some kink folds occur which might be related to folding of the Kokoweef syncline. The main difference with crystalline basement in the Mesquite Mountains antiform is the highly sheared nature of the basement in the Kokoweef syncline (Fig. 24).

Of great significance in understanding the Kokoweef syncline is the nature of the basement-cover contact (Precambrian-Cambrian unconformity).
Figure 24a. Sheared basement in Kokoweef syncline. Elongate quartz (white) warping around feldspar porphyroclasts. (Mag. 4X, plain light).

Figure 24b. Sheared basement in Kokoweef syncline. White is elongate quartz. (Mag. 4X, plain light).
As in the Mesquite Mountains antiform the contact is depositional and little or no evidence of bedding-parallel shear or slip was seen anywhere along it (Fig. 23). Foliation in the basement usually makes a high angle with the contact and sometimes becomes slightly more sheared near the contact. Unlike the Mesquite Mountains antiform, the Tapeats-basement contact is definitely folded (Fig. 21). Also, the contact is cut by a number of faults of small displacement (some of which are not shown on Figure 20).

The Kokoweef syncline is in many ways similar to the Mesquite Mountains antiform and a similar problem arises. That is—how is the basement involved in folding when no slip occurs along the basement-cover contact. Three possible mechanisms must again be considered in explaining adjustment of the basement during folding of the sedimentary cover: 1) the basement folded with the cover, 2) the basement adjusted by pervasive or spaced shear, or 3) the basement adjusted by rigid rotation. The first mechanism can be discarded again because the basement does not fold on the scale of the Kokoweef syncline. The third mechanism cannot entirely explain behavior of the basement because the basement-cover contact is folded into a tight overturned fold.

These facts, plus possible shearing in the basement and faulting of the basement-cover contact, favor the second mechanism. However, one major problem exists. This mechanism would require considerable shortening of the basement during folding of the cover. Basement rocks in the Kokoweef syncline are more sheared and flattened than basement seen elsewhere in the Clark Mountains. Also the foliation is approximately parallel to an axial plane of the fold. However, post-tectonic garnets seen in some thin sections are growing across the foliation. Also the amount of strain and recrystallization seen in the Tapeats sandstone (see Fig. 22)
is incompatible with the strain and metamorphic grade seen in the basement rocks (see Fig. 24). (Although this orthoquartzite does show the effects of annealing recrystallization, other lithologies in the Tapeats, such as a basal conglomerate [see Fig. 23], show little or no strain). Therefore, although formation of the syncline appears to be temporally related to intrusion of the nearby Ivanpah pluton, latest (?) strain and recrystallization in the basement rocks possibly pre-dates formation of the fold. Thus any shearing that occurred during folding of the cover was not pervasive on a small scale.

I believe that some combination of mechanisms two and three must have acted in deforming the basement. That is some spaced shearing which probably localized itself along the fold limbs by reactivating an old (Precambrian) foliation.

It seems inconsistent that shearing could have occurred in basement rocks identical to those that deformed by rigid rotation in the Mesquite Mountains antiform under the same (?) conditions. However, there are two reasons that might explain this inconsistency. First, the Mesquite Mountains antiform probably formed after Keystone thrusting whereas the Kokoweef syncline formed prior to thrusting of the Keystone plate. From complex relationships north of New Trail Canyon, Burchfiel and Davis (in prep.) have interpreted the Kokoweef syncline as having formed in response to east-directed parautochthonous thrusting prior to Keystone thrusting. Thus the local stresses which probably resulted in these two structures were approximately horizontal in one case (Kokoweef syncline) and approximately vertical in the other (Mesquite Mountains antiform). However, this fact alone is not reason enough to explain the variability in structural style exhibited in the basement of the Clark Mountains area. A second, and more fundamental reason, lies in the aspect of scale.
Foliations in basement of the Clark Mountain thrust complex are generally steep but some large scale folding is exhibited in the Mesquite Mountains area. The result of this folding is shown in the Mesquite Mountains antiform where basement behaved homogeneously and isotropically and rotated as a rigid block. However, as shown by Petterson and Weiss (1961), scale is implicit in the definition of basement, particularly as used by Prucha and others (1965) and Stearns (1970). This is illustrated for the Clark Mountain area in Figure 19. Basement in the Kokoweef syncline was thus oriented such that, at the scale of the fold, it acted heterogeneously and anisotropically. Shear stresses were set up across foliation planes during horizontal shortening of the overlying paraautochthon.
HYPOTHESES OF CAUSES OF FORELAND DEFORMATION

It is not the purpose of this study to solve the unclear origin of basement uplifts and drape folds. However a brief discussion of the proposed origins of basement uplifts in the Wyoming Province will help to elucidate the possible mechanisms of basement involvement in the Clark Mountains, and how this involvement is related to foreland deformation.

The Wyoming Province is the most extensive area of foreland basement deformation known along any orogenic belt in the world (Lowell, 1974). Block uplifts characteristic of this province were caused by faults that exhibit extreme variability in orientation, both between ranges and along strike. Orientations range from low-angle thrusts (for example along the west flank of the Wind River Range), to high-angle normal and reverse faults (for example at Rattlesnake Mountain and the Beartooth Plateau respectively). Because of this variability, different geologists have tried to explain each uplift with a different hypothesis.

Despite the geometric variability of these uplifts, the extensive occurrence of basement uplifts in the Wyoming Province must be related to some regional mechanical system. Because the evidence for horizontal compression, vertical movement, and wrench or strike-slip movement in the Wyoming Province is well substantiated (Lowell, 1974), no single uplift geometry can be used to determine this regional system. Also because none of these three mechanical systems seem to account for the structural complexity of uplifts in the Wyoming Province, some combination of them must have been active during Laramide time.

For many years it was believed that uplifts in the Wyoming Province were predominantly vertical block uplifts bounded by high-angle faults.
Berg (1962), recognizing the variability in fault orientations, proposed that such uplifts formed by one of three mechanisms: block uplift, thrust uplift, or fold-thrust uplift, preferring the last. However he believed (p. 2028) that the fold-thrust mechanism suggests "extreme deformation of the Precambrian crystalline rocks as opposed to the rigid basement of both block and thrust uplift" and that this deformation suggests "plastic deformation at relatively shallow depths." These statements are in contrast to both experimental data (cited above) and to direct observations in the Wyoming Province (Stearns, 1970).

Woodward (1976) has summarized some of the major hypotheses that have further attempted to explain driving mechanisms (probably related to deep crustal processes) for the proposed regional systems (or combinations of them) mentioned above. He believes that isostatic rise of large amounts of sialic crust, moved by metamorphic flowage from the west, can account for the Rocky Mountain basement uplifts. Burchfiel and Davis (1975) have suggested that rise of hot magmas generated from a shallow-dipping subducting oceanic plate has caused the basement uplifts of the Rocky Mountains. Although the patterns of Laramide igneous activity and basement uplifts do not correspond closely, they speculate that diapiric movement of plutons into the thermally weakened lower crust along with some horizontal crustal compression is the driving mechanism for the uplifts. Lowell (1974) suggests vertical maximum compressive stresses produced from bouyancy of an underthrust lithospheric slab (based on data from Lipman and others, 1971) along with lesser horizontal compressive stresses produced from subduction to the west, were combined to cause the Rocky Mountain uplifts.

Any hypothesis used to explain foreland deformation in the Wyoming Province must account for the dominant vertical movements (both absolute
up and down) in a regional stress field that is at least partially compres-
sional (tangential). Hafner (1951) has demonstrated through theoretical
analysis that a single set of boundary conditions can lead simultaneously
to potential faults of varying orientation as observed in the Wyoming
Province. Geologically the boundary conditions he used were as follows
(Stearns, 1975):

1. deep within the crust there exists an upwelling and downwarping,
2. this creates a frictional drag of varying magnitude along the
   bottom of the block,
3. the horizontal component of pressure increases linearly with
   depth, and
4. there is no frictional drag along the Earth's surface.

Through the same type of analysis, Couples (pers. communication, 1976)
has produced fault orientations similar to those seen in uplift structures
in the Wyoming Province using different sets of boundary values. All of
Couples' solutions require some sort of differential vertical load in-
duced on the base of the block. These boundary conditions are local
manifestations of some regional stress system. Again, this system can-
not be deduced from any single uplift geometry.

Relation of Clark Mountains to
Rocky Mountain Foreland Deformation

This study documents one of the only areas in the southern Cordil-
leran foreland where basement rocks are involved in foreland deformation.*

*The only other area in the southern Cordillera that I know of that ex-
hibits a similar style of foreland deformation is in the Muddy Mountains,
southern Nevada (pers. communication, D. W. Stearns, 1976). A student
from Texas A & M University is currently studying this area.
Also, the Clark Mountain complex exhibits two different styles of foreland basement involvement, one of which is analogous to foreland deformation in the Wyoming Province. Because this style of foreland deformation is pervasive on a large scale in the Wyoming Province, the question arises: Why is this style of basement deformation not more pervasive in the Cordilleran foreland of southeastern California? Three possible answers exist. First, more structures of this type are present but have not been recognized as yet, possibly as a result of the level of erosion. Many of the Basin-Range faults could have caused drapes over them, and the resultant sedimentary drape folds in the ranges completely eroded. This does not seem likely, as almost no basement rocks are exposed in these ranges.

Second, the Mesquite Mountains antiform could be a fortuitous occurrence associated with Basin and Range faulting (or wrench faulting). However, assuming that Basin and Range faulting affected rocks under essentially the same conditions, one would expect similar structures throughout the province.

Third, and most likely, some controlling factor, or set of controlling factors, has caused similar style uplifts, although in different abundance, in two areas of the Cordilleran foreland. This implies some fundamental difference in factors between the two areas. Some of the possible factors controlling similarities and differences between the Wyoming Province and the Clark Mountain area are discussed below.

Of prime importance in causing the Wyoming Province style of deformation is the mechanical behavior of the basement and sedimentary cover. As discussed above, basement in the Mesquite Mountains antiform acts as a brittle material and deforms by faulting and rigid rotation whereas the sedimentary cover behaves more or less as a ductile material and folds. However
not all of the sedimentary cover in the Mesquite Mountains antiform deformed in a ductile fashion, as the Ivanpah fault has cut through the entire Keystone thrust plate and part of the Mesquite Pass thrust plate. This brittle behavior of the sedimentary cover is probably due to the greater thickness of the cover in the Clark Mountains than at Rattlesnake Mountain (Fig. 9). Thus, fewer drape folds formed possibly because of the greater thickness of cover.

The frontal Keystone thrust plate probably moved over an erosion surface (Burchfiel and Davis, in prep.) prior to formation of the Mesquite Mountains antiform. If this erosion surface acted as an avenue of pore fluid escape from the base of the sedimentary cover, then the effective confining pressure would be increased. The higher lithostatic load and possibly higher effective confining pressure in the cover of the Mesquite Mountains antiform might explain why the cover acted partially in a more brittle manner than at Rattlesnake Mountain.

Behavior of the basement, as affected by both depth of burial and by mechanical anisotropy, might also be a controlling factor. Precambrian basement in the Wyoming Province is commonly "granitic" and less foliated than the well-foliated Precambrian basement in southeastern California. The dependence of the structural style of foreland basement involvement on anisotropy is seen in the Clark Mountain area and has been demonstrated in this study (Fig. 19). The basement in the Mesquite Mountains antiform acted in a brittle manner on the scale of the structure (see Fig. 19a) due to Precambrian folds that prevented Mesozoic or Cenozoic folding through pervasive slip along shear planes as took place in the Kokoweef syncline (see Fig. 19b). Thus the behavior of basement is controlled by its mechanical properties and not necessarily by its lithology. The inherent anisotropy of basement in this region might
explain the lack of pervasively developed basement uplifts in southeastern California.

The position of the two areas (Wyoming Province and southeastern California) along the Cordilleran foreland relative to regional tectonic elements could have a large effect on the nature of their structural development. During Late Mesozoic to Early Tertiary time the western continental margin was overriding oceanic crust to the west. Prior to Laramide time (late Cretaceous to Eocene) subduction along this boundary generated the Sierran volcanic-plutonic arc, and during Laramide time, when the basement uplifts developed in the Wyoming Province, subduction-derived (?) igneous activity shifted eastward to the Rocky Mountains. The formation of basement uplifts in the Wyoming Province and the Clark Mountains was probably related to some thermally-activated deep crustal (or upper mantle?) process (Burchfiel and Davis, 1975; Woodward, 1976). However the style of allochthonous basement involvement and the superposition of early and late Mesozoic igneous activity in the Clark Mountains is indicative of a high ductility zone which probably controlled thrusting and foreland deformation in the area (Armstrong and Dick, 1974; Burchfiel and Davis, 1975). The Kokoweef syncline formed at this time very close to the east edge of the thermally activated area. This position would explain how the basement in the syncline has deformed by pervasive (?) and spaced shear (the orientation being controlled by the foliation). Also, this high ductility zone could have prevented pervasive (if any) differential vertical uplift of the basement on the scale of the Wyoming Province during this time.

Timing of foreland basement uplift relative to orogenic activity is also possibly a controlling factor. Laramide uplifts in the Wyoming Province occurred near the end of and probably after Sevier thrusting.
The Mesquite Mountains antiform might have developed near the end of or after Sevier thrusting or it might have formed much later.

In summary, the formation of drape folds over basement uplifts is probably dependent on a number of controlling factors. These factors, including the mechanical properties of basement and cover, the foreland position of uplifts relative to regional tectonic elements, and the timing of uplifts relative to orogenic activity, are all interrelated. Although the occurrence of drape folds is affected by these factors, the ultimate cause of such structures is dependent on local boundary conditions. This is because basement uplifts with associated drape folds can theoretically form in any tectonic setting.
SUMMARY AND CONCLUSIONS

The Clark Mountain thrust complex contains two structures (Mesquite Mountains antiform and Kokoweef syncline) which involve autochthonous rocks and exhibit two different styles of crystalline basement involvement in foreland deformation. The Mesquite Mountains antiform is analogous to well-studied basement uplifts and associated drape folds in the Wyoming Province. Figure 25 summarizes the significant similarities and differences between the Mesquite Mountains antiform and drape structures in the Wyoming Province. Basement in the Mesquite Mountains antiform, which deformed by rigid rotation, acted as an active or forcing member over which the sedimentary cover passively draped. Basement in the Kokoweef syncline adjusted partially by shearing in response to folding of the sedimentary cover.

A number of significant conclusions can be drawn from this study:

1. This study documents the occurrence of foreland basement deformation in the southern Sevier orogenic belt. The Mesquite Mountains antiform is the first drape structure documented outside of the Wyoming Province.

2. Autochthonous basement deformation exhibits two styles of involvement in the Clark Mountain complex. This difference in style depends on mechanical behavior of both basement and sedimentary cover.

3. The Mesquite Mountains antiform is analogous to similar structures in the Wyoming Province. The development of basement uplifts and associated drape structures possibly occurred at a similar time relative to the same type of orogenic activity in each area.
<table>
<thead>
<tr>
<th>Features of drape structures</th>
<th>Mesquite Mountains antiform</th>
<th>Wyoming Province (Rattlesnake Mtn.)</th>
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<tr>
<td><strong>1. BASEMENT</strong></td>
<td></td>
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<tr>
<td>Rock type</td>
<td>Precambrian foliated gneisses</td>
<td>Precambrian granitic rocks</td>
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<tr>
<td>Deformation</td>
<td>faulting and rigid rotation</td>
<td>faulting and rigid rotation</td>
</tr>
<tr>
<td>Mechanical behavior</td>
<td>homogeneous and isotropic</td>
<td>homogeneous and isotropic</td>
</tr>
<tr>
<td><strong>2. SEDIMENTARY COVER</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock types</td>
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<td>thin basal sandstone and shale&lt;br&gt;below thick carbonates</td>
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<td>Thickness</td>
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<td><strong>3. FEATURES</strong></td>
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<td>Cambrian Bright Angel Shale</td>
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<tr>
<td>Cataclasis</td>
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<td>minor, on corners of basement blocks</td>
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<tr>
<td>Internal deformation in cover</td>
<td>little or none</td>
<td>little or none</td>
</tr>
</tbody>
</table>

Figure 25 Comparison of features of Mesquite Mountains antiform with features of drape structures in the Wyoming Province.
This indicates that similar mechanical controls affected the development of Rocky Mountain style basement uplifts in the two areas.

4. The lack of prevasively developed basement uplifts in the southern Cordillera relative to the Wyoming Province could be a function of erosion or lack of recognition. It seems more likely that there must be some fundamental difference in the mechanical controls between the two regions.

5. Drape structures associated with basement uplifts are manifestations of local boundary conditions and not necessarily indicative of regional stresses.

6. Basement involvement in foreland deformation can occur through different mechanisms under the same(?) conditions, depending on certain parameters. Important parameters include scale, mechanical behavior of basement versus cover, timing, and tectonic setting, and these all are interrelated.
REFERENCES CITED


Bally, A. W., 1975, A geodynamic scenario for hydrocarbon occurrences: Proc. 9th World Petroleum Congr., v. 2, p. 33-44.


GEOLOGIC MAP OF THE MESQUITE MOUNTAINS ANTIFORM
SAN BERNARDINO COUNTY, CALIFORNIA
ERIC NELSON, 1976