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Geology of the Wilson Cliffs-Potosi Mountain Area, Southern Nevada

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Abstract

Detailed mapping of seven lithologic subunits in the Bonanza King Formation in the Wilson Cliffs-Potosi Mountain area, eastern Spring Mountains, Nevada, demonstrates the existence of two thrust plates between the NW-trending Cottonwood and La Madre faults. The structurally lower Wilson Cliffs thrust plate is thrust eastward along a spectacularly exposed contact juxtaposing nearly black Cambrian Bonanza King dolomite above white to pale red Jurassic Aztec Sandstone. This thrust has been called the Keystone thrust by previous workers, but the Keystone thrust can be traced from its type area in the Goodsprings District northward, where it forms the base of the Keystone thrust plate lying structurally above the Wilson Cliffs plate. The Wilson Cliffs plate is a remnant of the Contact thrust plate to the south and the Red Spring thrust plate to the north. Emplacement of the Contact-Wilson Cliffs-Red Spring thrust plate preceded the emplacement of the Keystone thrust and the two events are separated by movement on the La Madre fault and a period of erosion that locally removed the Wilson Cliffs plate. The Cottonwood fault displaces the Wilson Cliffs plate, but ends to the northwest by warping of the Keystone plate. The deformation along the Cottonwood fault can be explained by post-Keystone south-side-down displacement of 3500 to 3800 feet (1060 to 1150 m), and suggests that Cenozoic deformation may be more important within the Spring Mountains than currently recognized.

Presently the Contact-Wilson Cliffs-Red Spring thrust plate lies below and east of the Keystone thrust plate, a relationship that has been used to demonstrate that this part of the Cordilleran thrust belt did not become progressively younger eastward. However, at a low structural level, the ramp for the Keystone thrust fault lies east of the ramp for the Contact-Wilson Cliffs-Red Spring thrust fault and thus is in sequence. At a higher structural level, the Keystone thrust fault propagated across the Contact-Wilson Cliffs-Red Spring thrust plate, placing the leading edge of this plate east and below the surface trace of the Keystone thrust. Thus, the present map pattern gives the erroneous impression of an out-of-sequence relationship.

Introduction

THE KEYSTONE THRUST FAULT of southeastern Nevada is one of the best-exposed thrust faults in the world (Figs. 1 and 2). For more than half a century, geologic relations along the thrust fault and its lateral correlatives have been used: (1) as an example of typical geometric relations along the hanging wall and footwall of a ramp thrust (Serra, 1977); (2) to support various hypotheses for the mechanics of thrust faulting (Raleigh and Griggs, 1963; Johnson, 1981; Burchfiel et al., 1982; Price and Johnson, 1982; Axen, 1984); and (3) to establish timing relations between deformation in the hanging wall and footwall to show that in this part of the Cordilleran orogenic belt, thrust faults did not become progressively younger eastward (Longwell, 1926; Davis, 1973; Axen, 1984). Surprisingly, the best-exposed part of the thrust plate, where black and grey Cambrian dolomites over-

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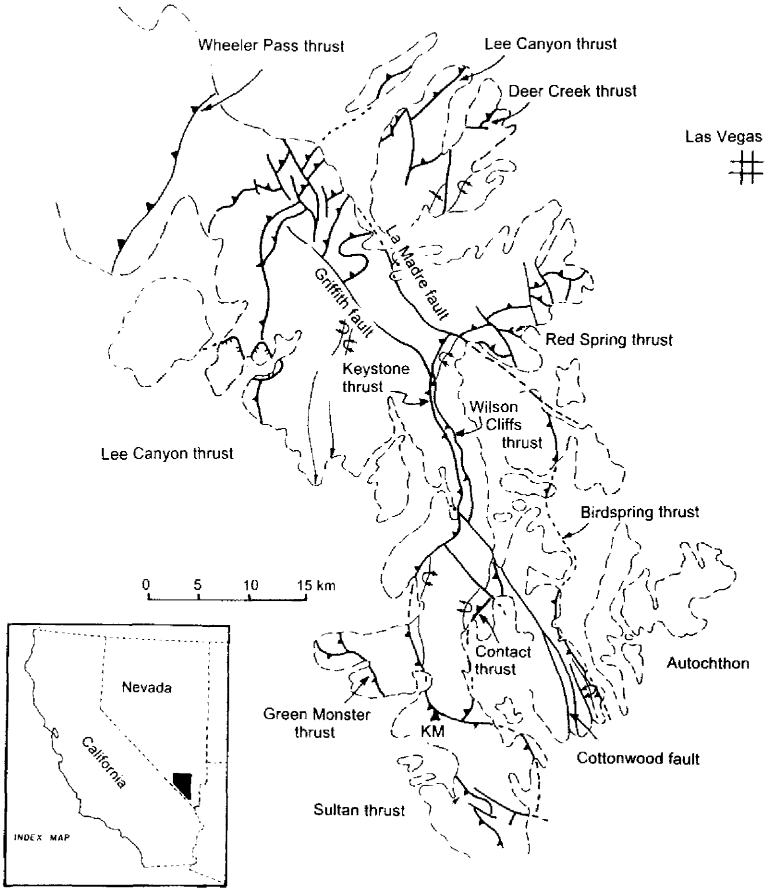

FIG. 1. Generalized tectonic map showing the major structural features of the eastern Spring Mountains, Nevada. KM locates the Keystone Mine, the type locality of the Keystone thrust fault. Inset map gives the location of the eastern Spring Mountains relative to Nevada and California.

lie white or tan Jurassic sandstone (Fig. 2), had not been mapped in detail. This paper presents results of mapping at a scale of 1:15,000 from the Red Rock Canyon area in the north to the Goodsprings mining district in the south.

Hewett (1931, 1956) first mapped and described the Keystone and structurally lower Contact thrust plates in the Goodsprings area immediately south of the area covered by this report (Fig. 1). The area at the Keystone Mine was designated as the type area of the Keystone thrust fault. Carr's (1983) restudy of the Goodsprings area has shown the complexity of structural events in that area, and he presented evidence that the Contact thrust is older than the Keystone thrust. Recent work by Fleck and Carr (1990) demonstrated that the Keystone thrust is younger than 100 ± 2 Ma, but the age of the Contact plate remains poorly constrained.

Longwell (1926) and Glock (1929) first mapped the Keystone and structurally lower Red Spring thrust plates in the northeastern Spring Mountains, north of the area covered in this report (Fig. 1). Longwell (1926) first concluded that the Red Spring thrust was older than the Keystone thrust, but later (1960) interpreted the two thrusts to be correlative and the complex relations between them to be related to thrusting contemporaneous with rotation and strike-slip displacement on the nearby Las Vegas Valley shear zone.

Davis (1973) restudied parts of the Red Spring thrust and concluded that Longwell's

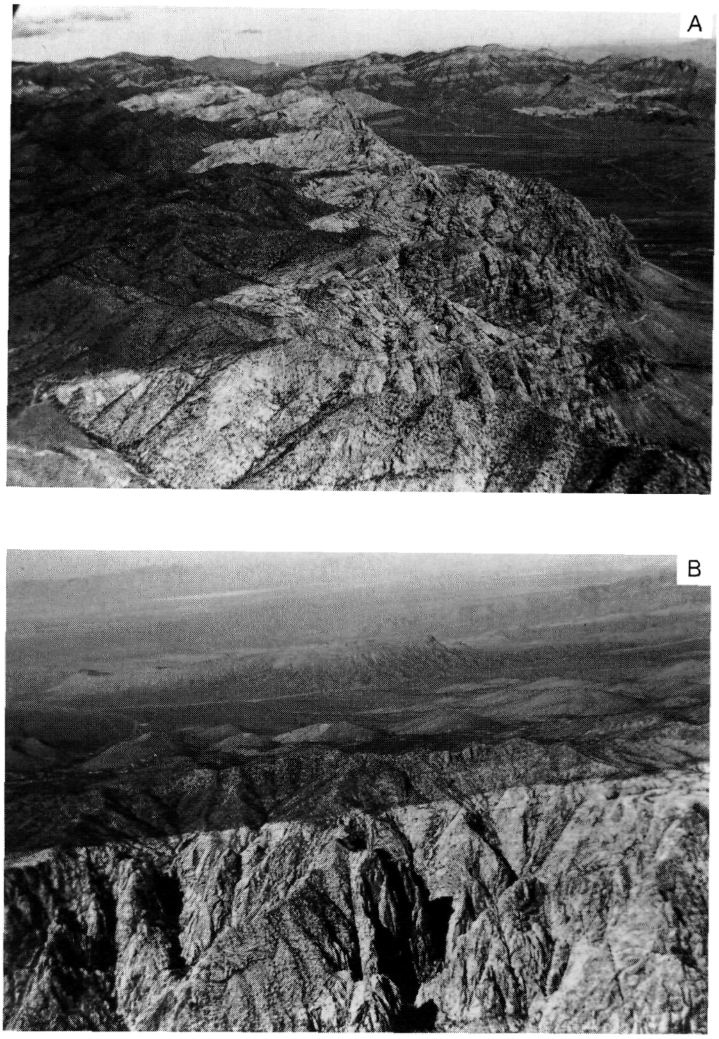

FIG. 2. Aerial photographs of the thrust fault at the top of the Wilson Cliffs. Light-colored rocks are the Jurassic Aztec Sandstone overlain along a planar thrust fault contact by dark Paleozoic rocks composed mostly of the Cambrian Bonanza King Formation. This thrust fault, commonly referred to as the Keystone thrust fault, is in fact the Wilson Cliffs thrust fault, which is structurally lower and older than the Keystone thrust fault. A. View looking north along the Wilson Cliffs thrust fault to the Red Rock Canyon area in the upper right. B. View looking west at the Wilson Cliffs thrust fault showing the distinctly planar character of the fault.

(1926) original interpretation that the Red Spring thrust pre-dated the Keystone thrust was correct. Davis also correlated the Red Spring and Contact thrusts and suggested they were remnants of a once continuous thrust. He further suggested that following the emplacement of the Red Spring–Contact thrust plate, it was cut by high-angle faults, uplifted on a horst block bounded by the Cottonwood and La Madre faults, and removed by erosion from the horst prior to emplacement of the structurally higher Keystone thrust plate (Fig. 1). Axen (1984, 1985) remapped in detail the area studied by Longwell, Glock, and Davis and concluded that the structural relationships support an older emplacement age for the Red Spring thrust plate relative to the Keystone plate, a concept challenged by Matthews (1988, 1989), but adequately defended by Axen (1989).

The area between the Goodsprings district and the northeastern part of the Spring Mountains was mapped by Secor (1962), and his mapping was incorporated into maps by Longwell et al. (1965) and Burchfiel et al. (1974) as part of more regional studies in the Spring Mountains. Their work was completed before the structural complexities of the adjacent two areas had been realized. Our mapping of the Wilson Cliffs-Potosi Mountain area was done at scales of 1:15,000 and 1:24,000 as part of detailed studies of thrust faults in this region to better understand their geometry and timing, as well as the character of the thrust surfaces in relation to hanging-wall and footwall rocks, and to set realistic boundary conditions for mechanical studies of the thrust faults in this area and thrust faults in general. The Potosi Mountain area was mapped by Cameron (1977) and the Wilson Cliffs area was mapped later by Burchfiel and Royden. One of the results of this study is that the well-exposed thrust fault at the top of the Wilson Cliffs—and described by all previous works as the Keystone thrust fault—is, in fact, not the Keystone thrust. This conclusion will be documented and some of its ramifications presented below.

Stratigraphy

The oldest rocks exposed in the Wilson Cliffs-Potosi Mountain area are limestone and dolomite of the Middle and Upper Cambrian Bonanza King Formation. Seven informal subdivisions of this formation were made for mapping purposes to show the geometry of the thrust faults in the area relative to hanging-wall and footwall rocks. Detailed mapping of these units has revealed that there are two major thrust faults present throughout the mapped area, and that the structurally lowest thrust fault, which places Cambrian rocks above the Jurassic Aztec Sandstone, is not the Keystone thrust. To document the stratigraphic level at which the two thrust faults in the map area detached, it is necessary to discuss the stratigraphy of the Bonanza King and older formations from the Las Vegas-Spring Mountains region beyond the limits of the mapped area. Younger parts of the stratigraphic sequences ranging from Ordovician to Jurassic are adequately described in the studies by Cameron (1977), Gans (1974), Axen (1984, 1985), and Carr (1983) and will not be presented here.

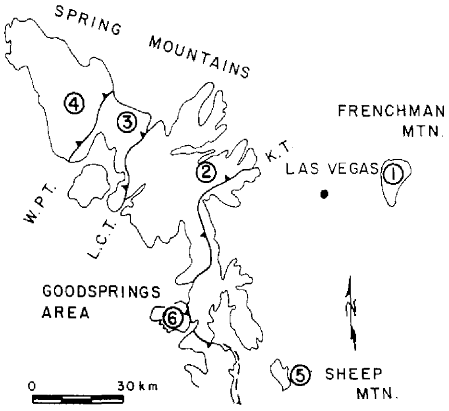

FIG. 3. Location of sections (Figs. 4A and 4B) within the craton, Keystone thrust plate (KT), Lee Canyon thrust plate (LCT), and Wheeler Pass thrust plate (WPT).

Tapeats Sandstone-Zabriskie Quartzite

East of the Spring Mountains at Frenchman Mountain and at Sheep Mountain (Figs. 3 and 4) the Lower Cambrian Tapeats Sandstone rests unconformably on Precambrian metamorphic rocks (Hewett, 1956; Longwell et al., 1965). The Tapeats Sandstone is ~50 meters thick and consists of red, tan, and white quartzite; quartz-rich sandstone; and conglomerate. The rocks at Frenchman and Sheep mountains lie east of the Cordilleran thrust belt and are part of the North American cratonal succession.

Rocks correlative to the Tapeats do not crop out in the eastermmost thrust faults of the Cordilleran thrust belt because detachment of these faults occurred at a higher stratigraphic level. Farther west, rocks correlative to the Tapeats crop out in the Wheeler Pass thrust plate (Figs. 3 and 4). Work by Stewart (1970) demonstrated that within these thrust plates, a conformable succession of Upper Precambrian and Cambrian sedimentary rocks is present, and that the Zabriskie Quartzite and the uppermost part of the Wood Canyon Formation, both of Early Cambrian age, correlate with the Tapeats. The thickness of the Lower Cambrian

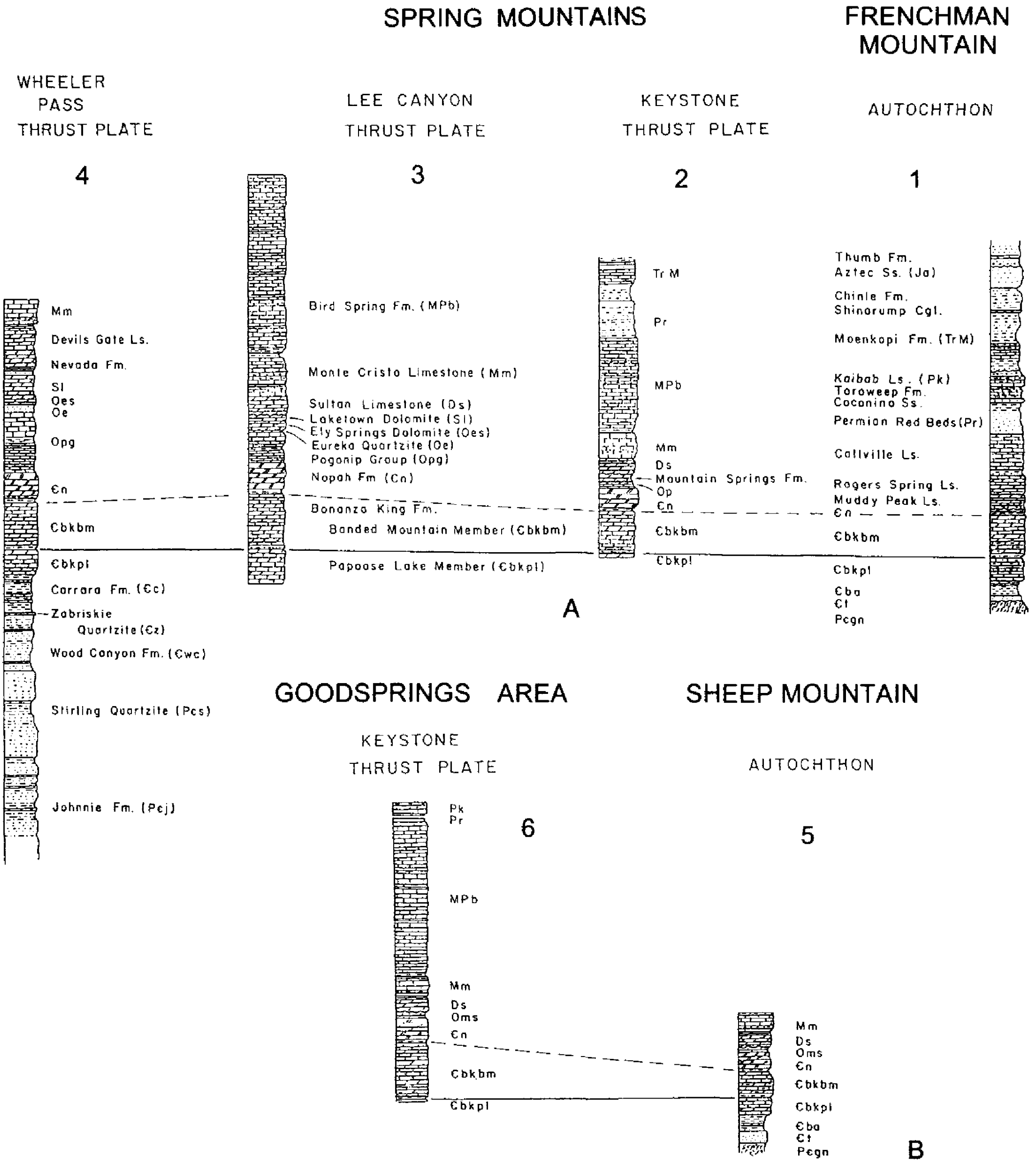

FIG. 4. Stratigraphic sections from cratonal areas east of the Spring Mountains (Frenchman Mountain and Sheep Mountain) to miogeoclinal sections in different thrust plates in the Spring Mountains. A. Spring Mountains and Frenchman Mountain. B. Goodsprings area and Sheep Mountain. Units discussed in the text are the Tapeats Sandstone (Єt), Bright Angel Shale (Єba), and the Bonanza King Formation and its two members—the lower, Papoose Lake Member (Єbkpl) and the upper, Banded Mountain Member (Єbkbm). Even though the Papoose Lake Member is not fully present, and older units are not exposed within the eastern Spring Mountains, their presence can be confidently inferred because of the correlation of units in detail from the craton to the miogeocline in the western part of the Spring Mountains.

rock sequence and the conformable addition of the Upper Precambrian sedimentary rocks beneath the Lower Cambrian rocks toward the west indicate the presence of a depositional hinge zone between cratonal and miogeoclinal rock sequences. This hinge zone has been telescoped by E-directed Mesozoic thrust faulting and it cannot be accurately reconstructed because transitional rock sequences are not exposed in the Las Vegas region.

Bright Angel Shale-Carrara Formation

Conformably above the Tapeats Sandstone in the cratonal section, and above the Zabriskie Quartzite in the miogeoclinal section, is a sequence of green calcareous shale and fine-grained quartz-rich siltstone, with beds of grey, mottled limestone that commonly contain round to elliptical algae pisolites ranging up to 5 cm in diameter. Maroon shale and orange-weathering silty limestone also are present. In the cratonal areas of Frenchman and Sheep mountains, these rocks are ~100 to 150 m thick, and they are assigned to the Lower and Lower Middle Cambrian Bright Angel Shale (Figs. 3 and 4); (Hewett, 1956; Longwell, 1965). Within the Wheeler Pass thrust plate, correlative rocks are 300 to 400 m thick and are assigned to the Carrara Formation (Figs. 3 and 4) (Burchfiel and Davis, 1971; Burchfiel et al., 1974). At the tops of both formations, mottled, silty limestone becomes progressively less silty through about 5 to 15 m and grades into dark grey, mottled limestone and dolomite at the base of the Bonanza King Formation. Like the Tapeats Sandstone, transitional rocks of the Bright Angel Shale (cratonal section) and Carrara Formation (miogeoclinal section) are not exposed in the Las Vegas region.

Bonanza King Formation

Conformably above the Carrara Formation and Bright Angel Shale, both in the miogeoclinal and cratonal sequences, is a thick succession of limestone, dolomite, and silty dolomite of Middle and early Late Cambrian age that was assigned to the Bonanza King Formation of Hazzard and Mason (1936) by Gans (1974). The Bonanza King Formation is the oldest formation that crops out at the base of the easternmost thrust faults in the Cordilleran thrust belt in this region.

Identification and mapping of seven units in the upper part of the Bonanza King Formation has been the key to unraveling the complex structure of the Wilson Cliffs-Potosi Mountain area. In addition, regional correlations show that both major thrust faults recognized in the mapped area detached along basal decollements that were within the lower part of the Bonanza King Formation and not within the shales of the underlying Bright Angel-Carrara interval (Burchfiel et al., 1982).

The Bonanza King Formation of Hazzard and Mason (1936) was subdivided into two members—the lower, Papoose Lake and upper, Banded Mountain members—by Barnes and Palmer (1961). Since their subdivision, these two members have been recognized and mapped regionally throughout the Las Vegas-Death Valley area (Figs. 3 and 4). In the eastern Spring Mountains and adjacent areas, subdivisions of the members have been identified and widely correlated (Fig. 5) (Gans, 1974), but not mapped areally.

Papoose Lake Member. The Papoose Lake Member of the Bonanza King Formation consists of medium to dark grey limestone and dolomite. Characteristically the limestone and dolomite form irregularly bedded to mottled interbeds 1 to 5 cm thick. Also present is thin-bedded to laminated, medium to dark grey limestone and rare beds of pisolitic or oolitic limestone. Very rare beds of grey to light grey laminated or wavy bedded limestone are present as well. The main rock types occur in units 2 to 20 m thick that crop out as subdued ledges and benches, with the thin-bedded and laminated limestone forming the more recessive units.

In cratonal sections, the Papoose Lake Member is about 100 to 150 m thick at Frenchman Mountain and about 150 to 200 m thick at Sheep Mountain (Figs. 3 and 4). In both places, its top is poorly defined because the basal rocks of the overlying Banded Mountain Member are not as typically developed as they are where the two members were first defined. Within the Wheeler Pass thrust plate, in the miogeoclinal section, the Papoose Lake Member is 200 to 250 m thick and contains rare thin units of white-weathering, laminated dolomite and silty dolomite. The upper part of the Papoose Lake Member also is present in the Lee Canyon and Green Monster thrust plates that structurally overlie the Keystone plate (Figs. 1, 3, and 4). Thus, in regional correlations it is clear that rocks equivalent to the Papoose Lake Member were present in the eastern Spring Mountains, but only the upper few tens of meters of the Papoose Lake Member crop out locally at the base of the two thrust plates in the Wilson Cliffs-Potosi Mountain area.

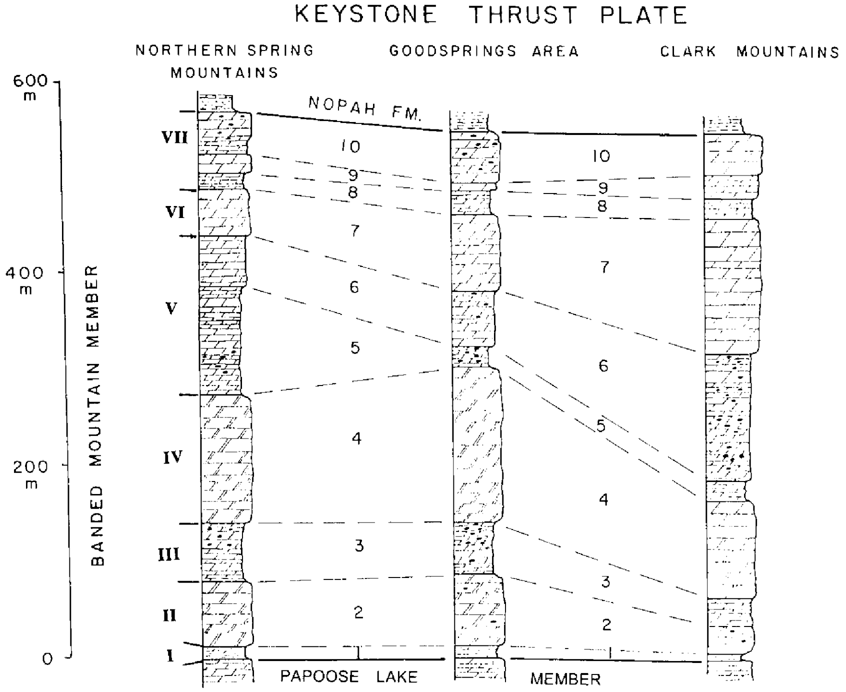

FIG. 5. Subdivisions of the Banded Mountain Member of the Bonanza King Formation from the northern Spring Mountains through the Goodsprings area (covered in this report) to the Clark Mountains, California, 60 km farther south. Detailed stratigraphy by Gans (1974) demonstrated that the Banded Mountain Member could be subdivided into the 10 units shown in this figure. These 10 units can be correlated for more than 100 km along the eastern part of the Spring Mountains to the Clark Mountains. For mapping purposes, we found that seven subdivisions (shown in roman numerals) were more useful, because some of the units described by Gans were difficult to follow in structurally complex areas.

Banded Mountain Member. The Banded Mountain Member of the Bonanza King Formation consists of alternating units (50 to 100 m thick) of dark and light grey dolomite that give the member its distinctive banded outcrop appearance. These bands have been subdivided into seven informal units that were mapped during this study to decipher the internal structure within the Bonanza King Formation (Fig. 5). By mapping these units, we were able to determine the existence of two major thrust faults in the Wilson Cliffs area, to demonstrate that the detachment of both thrust plates occurred within the Bonanza King Formation and not within the underlying Bright Angel Shale, and to show that the internal structures of the two thrust plates are quite different.

The thickness of the Banded Mountain Member is uncertain, varying between 400 and 500 m. Most of the variation in thickness is related to numerous faults that cut bedding at a low angle. From a distance, the light and dark units of the Banded Mountain Member appear to be continuous and in many places structurally simple, but in detail there are numerous small repetitions of beds or groups of beds within each unit along faults that cut bedding at angles from 5 to 15°. Most of these faults could not be mapped at a scale of 1:15,000 because in some cases their displacement is small and they could not be traced along strike. However, their presence is clear and makes the detailed stratigraphy (at a scale of tens of meters) in each unit uncertain. Some variations in thickness may be the result of deposition, particularly where low-angle faults could not be observed, but many of these faults are so subtle that they could be detected only where the outcrop is excellent. Seven units were mapped in the Banded Mountain Member, which correlate generally with the

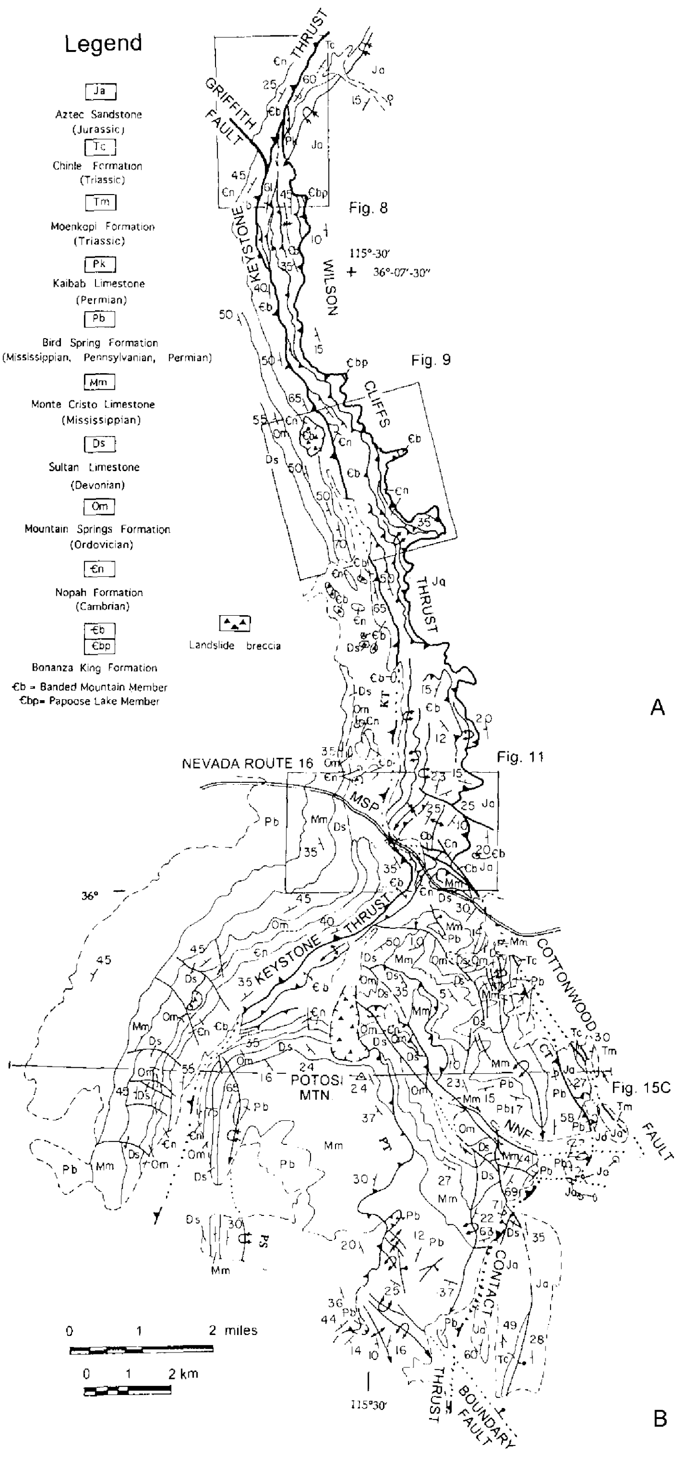

FIG. 6. Generalized geologic map of the Wilson Cliffs-Potosi Mountain area, Nevada. Location of detailed Figures 8, 9, and 11 are shown, as is the location of the geological cross section in the Potosi Mountain area (see Fig. 15C). Abbreviations: CT = Contact thrust; KT = Keystone thrust; MSP = Mountain Springs Pass; NNF = Ninety-Nine fault zone; PS = Potosi syncline; PT = Potosi thrust.

10 units identified by Gans (1974). It will be noted in the descriptions below where our units differ from his. On the generalized geological map (Fig. 6), these units are not distinguished, but they are shown on Figures 8, 9, and 11, which are parts of a detailed map of the Wilson Cliffs–Potosi Mountain area at 1:15,000.[1]

The basal unit, Unit I, consists of 10 to 15 m of yellow- to orange-weathering, thin-bedded to laminated, fine-grained silty dolomite. This unit is known to most local geologists as the "silty unit." It is easily recognized by the formation of orange-weathering slopes within the otherwise light and dark grey dolomite succession. The base of this unit is the contact between the two members of the Bonanza King Formation.

Unit II consists of ~30 to 50 m of grey dolomite and dark grey limestone in irregular or mottled beds 2 to 5 cm thick. This unit and the higher two dark grey, mottled units (Units IV and VI) form rugged cliffs between more slope-forming, lighter grey banded units with mixed rock types. Unit II, unlike units IV and VI above, locally contains beds of light grey mottled and laminated dolomite. In some places it can be demonstrated that these beds are faulted into the sequence, but in other places they appear to be stratigraphically part of Unit II.

Unit III is formed predominantly by a light and medium grey, generally slope-forming, sequence that consists of several different interbedded rock types. Light grey to nearly white laminated dolomite forms beds 10 cm to 1 m thick and alternates with medium to dark grey dolomite that is thin to medium bedded, locally laminated, or mottled. Some beds contain large (10 to 50 cm) irregular grey chert nodules that weather with concentric grey, tan, and orange rings. The contrasting rock types in Unit III appear to facilitate the development of small faults that cut bedding at low angles and duplicate or eliminate section. Thus, the thickness of these units varies considerably along strike. The interbedding of different rock types makes it easy to recognize the faults. Unit III varies in thickness between 50 and 150 m, and its true thickness may be ~50 m.

Unit IV is a cliff-forming, uniform dark grey, mottled limestone and dolomite. Of the dark mottled units within the Bonanza King Formation, it is the darkest and most uniform in composition. Minor rock types present all are dark grey and include thin beds of flat-pebble conglomerate, laminated dolomite, and dolomite with rare wispy stringers of white dolomite 1 to 2 cm long. Unit IV varies from 75 to 200 m in thickness, and its original thickness probably is ~100 to 150 m.

Unit V is similar to Unit III and consists of dominantly slope-forming light and medium grey sequences of different rock types. The dominant rock types are the same as those of Unit III, but also include laminated dolomites with algal heads of 5 to 30 cm in diameter, pisolitic and rare oolitic dolomite, and beds with vertical worm tubes up to 10 cm long. Unit V also contains large chert nodules at several horizons. Some beds of dark grey, mottled dolomite similar to Units II, IV, and VI are present, but they never reach the thickness of these three units. Unit V varies from 50 m to more than 300 m in thickness; its true thickness is difficult to determine because it is the locus of numerous faults and folds. We estimate a thickness of 200 to 250 meters for Unit V, which in our scheme correlates approximately with Units 5 and 6 of Gans (1974).

Unit VI is the highest cliff-forming, dark grey, mottled limestone and dolomite in the Banded Mountain Member. Like Unit IV, it is quite uniform in lithology and can be distinguished from Unit IV by its slightly lighter grey color. In the southern part of the area, the color is a dark grey with a distinctive brown tint. Unit VI varies from 30 to 200 m in thickness and its original thickness is ~75 to 100 m. However, it may have been 150 m thick in the southern part of the mapped area. Our Unit VI corresponds approximately to Unit 7 of Gans (1974).

Unit VII is the most variable unit in the Banded Mountain Member. Within the lower thrust plate of the Wilson Cliffs area, it consists of a basal section of well-bedded, light grey, mottled dolomite; light grey to white laminated dolomite; and rare beds of grey to dark grey dolomite that contain 1- to 5-cm-long wispy stringers of white dolomite. The upper part of Unit VII is a massive to well-bedded sugary dolomite with some rare stringers of silty dolomite. Within the upper thrust plate, Unit VII

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[1] This detailed map can be obtained by contacting Doug Walker at the University of Kansas (email address: jdwalker@kuhub.cc.ukans.edu).

consists of only poorly bedded to massive, medium- to coarse-grained, white to very light grey dolomite. In the upper thrust plate, Unit VII is ~30 to 70 m thick, whereas in the lower thrust plate it is 100 to 150 m thick. Our Unit VII corresponds approximately to Units 8, 9, and 10 of Gans (1974).

Nopah Formation

The Nopah Formation of Hazzard (1937) was recognized by Gans (1974) in his revision of the Goodsprings Dolomite in the eastern Spring Mountains. Two members—a lower Dunderberg Shale Member and an upper unnamed member—were mapped during this study.[2] The Dunderberg Shale Member consists of 20 to 40 m of orange-weathering silty dolomite and rare green and tan shale with distinctive beds of grey limestone and brown dolomite 1 to 50 cm thick. The limestone beds characteristically contain abundant flat-pebble conglomerate. Lying gradationally above the slope-forming Dunderberg Shale, the upper member consists of cliff-forming, white, massive coarse-grained dolomite. The upper member is 100 to 150 m thick. Both members are present in the upper and lower thrust plates in the Wilson Cliffs-Potosi Mountain area.

Significance of the stratigraphic sequence

The Cambrian stratigraphy is important for two reasons. It shows (1) that initial detachment of both thrust faults in the map area took place within the lower part of the Bonanza King Formation; and (2) that subdivisions of the Banded Mountain Member can be mapped to determine the details of the local structure.

Considering the first point, Cambrian stratigraphic units can be recognized and show continuity from cratonal rocks east of the thrust belt at Frenchman and Sheep mountains to miogeoclinal rocks in the central and western Spring Mountains (Fig. 3). Because of this continuity and the gradual change in thickness and facies of these units, we infer that they originally had continuity throughout the eastern Spring Mountains. Units below the upper part of the Papoose Lake Member of the Bonanza King Formation are not exposed within the two thrust plates of the Wilson Cliffs-Potosi Mountain area because of thrust faulting. If the Cambrian units did have lateral continuity throughout this region before thrusting, the stratigraphic level at which the two thrust plates detached ranges from a few tens of meters below to about 100 m above the contact between the two members of the Bonanza King Formation (i.e., at the base of Unit I—the "silty unit"), and 200 to 300 m above the Bright Angel Shale (Fig. 7). There is no preferred detachment horizon within that part of the section. Perhaps even more surprising is the fact that both thrust plates detached within that interval even though they were emplaced at two different times: the lower plate was emplaced, cut by high-angle faults, and eroded before the upper plate was emplaced (see below). This level of detachment is present on a regional scale for correlative thrust plates that can be followed for ~100 to 150 km both north and south of the Wilson Cliffs-Potosi Mountain area (Burchfiel et al., 1982).

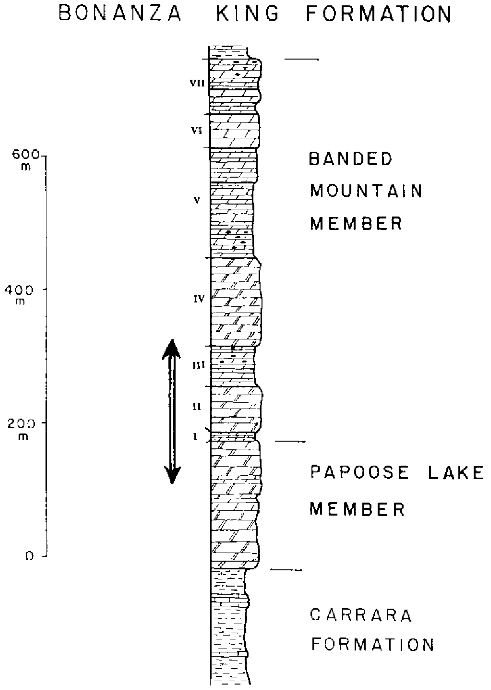

FIG. 7. Throughout the map area and beyond (Burchfiel et al., 1982), thrust faults along the eastern margin of the miogeocline detach within the Bonanza King Formation, from the upper part of the Papoose Lake Member to about Unit IV of the Banded Mountain Member (interval shown by the arrow to the left of the stratigraphic column).

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[2] The two members are not shown in Figure 6, but are shown on the detailed maps in Figures 8, 9, and 11.

Considering the second point above, we have shown that seven units can be mapped within the Banded Mountain Member. Gans (1974) demonstrated that stratigraphic subdivisions within the Banded Mountain Member could be correlated within the eastern Spring Mountains, but he did not attempt to map them. We have found a sevenfold subdivision to be most useful for mapping purposes (Fig. 5). This has allowed us to recognize the existence of two different thrust plates and to demonstrate that they contain two different structural styles.

Structure

Detailed mapping in the area between the Cottonwood and La Madre faults demonstrates the presence of two major thrust plates lying above the Jurassic Aztec Sandstone of the Wilson Cliffs (Figs. 1 and 6). The structurally lower thrust plate places the Cambrian Bonanza King Formation above the Jurassic Aztec Sandstone (Fig. 6). This thrust plate, called the Keystone plate by earlier workers, is spectacularly exposed (Fig. 2) and has figured prominently in several models on the mechanics of thrust faulting (e.g., Longwell, 1926; Serra, 1977; Johnson, 1981; Burchfiel et al., 1982; Price and Johnson, 1982). Mapping by two of us (Burchfiel and Royden) demonstrates that this plate is not the Keystone thrust plate, and we refer to it here as the Wilson Cliffs plate. The higher thrust plate places the Bonanza King Formation above Cambrian dolomites of the Bonanza King and Nopah formations throughout much of the map area, but locally it rests on Mesozoic rocks in the northern part of the area (Fig. 6). The higher thrust plate is the Keystone plate, because it is continuous with the Keystone from its type area in the Goodsprings district to the south (Figs. 1 and 6). We also will show that the two thrust plates are of different ages. We correlate the Wilson Cliffs plate to the Contact-Red Springs plates (see below) and document, as Davis (1973) first suggested, that this plate once was continuous below the younger Keystone thrust plate and was emplaced before the higher Keystone plate. Products of the erosion that occurred in the interval separating emplacement of the two plates still are present in the northern part of the area. Sedimentary rocks also are present below the Wilson Cliffs plate, indicating that both thrust plates moved across erosion surfaces in the area where they are presently exposed.

Footwall of the Wilson Cliffs-Contact thrust plate

Rocks below the Wilson Cliffs-Contact thrust plate belong to the upper part of the structurally lower and more easterly Bird Spring thrust plate (Fig. 1). Throughout the map area they consist of the Jurassic Aztec Sandstone that dips 10 to 15° to the west. Because the Aztec contains abundant large-scale cross beds, attitudes on the map (Fig. 6) do not reflect the overall dip of the formation. Rarely, conglomerate is present—filling channels or as thin beds immediately below the Wilson Cliffs thrust. The channels, up to 3 m deep, consist of rounded pebbles and cobbles of quartzite set in a matrix of reworked Aztec quartz sand. The bedded conglomerates consist of pebbles of angular to rounded Cambrian and younger carbonate rocks, also set in a matrix of reworked Aztec quartz sand. The beds usually are no more than 20 to 30 cm thick and are poorly exposed. In the northern and central part of the area, the Aztec quartz-rich sandstone lies 3 to 5 meters below the thrust; it is white, dense, and composed of shattered and silicified material.

Excluding the high-angle faults discussed below, the only major structure in the footwall rocks within the map area is a NE-trending, E-vergent syncline in the northern part of the map area (Fig. 6). The west limb of the fold is overturned and rocks of the Triassic Chinle Formation are exposed. Toward the south, the axial trace of the fold trends obliquely to, and passes beneath, the Wilson Cliffs plate, but before it does, the western overturned limb of the fold is overlain by three thin thrust slices. The thrust slices consist of, in ascending order, redbeds of the Triassic Chinle and/or Moenkopi formations, limestone of the Moenkopi and Permian Kaibab formations, and Cambrian dolomite of the Wilson Cliffs plate (Fig. 8). This relationship, as well as the relationship of the fold to conglomerates discussed below, indicates that the fold is related to the emplacement of the Wilson Cliffs plate, not the higher Keystone plate, which overlies the fold in the northernmost part of the area. Throughout the

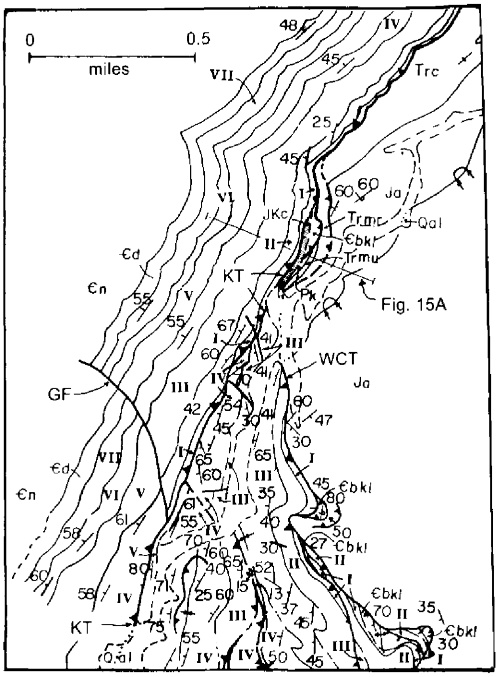

FIG. 8. Detailed geologic map of the northern part of the map area (for location, see Fig. 6). In this area, the Keystone (KT) and Wilson Cliffs (WCT) thrust faults merge. Units in the Banded Mountain Member (I through VII) are mapped separately and the uppermost part of the Papoose Lake Member (Єbkp) is present locally at the base of the Wilson Cliffs thrust plate. Above the overturned footwall syncline in the Jurassic Aztec Sandstone (Ja) are thrust slices of Kaibab Limestone (Pk), Moenkopi Formation lower limestone (Trmn), and upper redbeds (Trmr). They are overlain by a thin brecciated sheet of dolomite of the Papoose Lake Member, which we assign to the Wilson Cliffs plate. Lying west of these thrust slices and below the Keystone thrust is a narrow zone of bedded, reworked Aztec Sandstone interbedded with conglomerate composed of clasts of Bonanza King Formation and derived from the east (Jkc, shaded area). The eastern contact with the Wilson Cliffs plate is not exposed, but relations suggest that it was deposited on rocks of the Wilson Cliffs plate (see text). Other units mapped in the Keystone plate are Єd = Dunderberg Shale; Єn = upper Nopah Formation. The location of the cross section in Figure 15A is shown.

remainder of the area, the Aztec Sandstone is unfolded except by local small-scale folds below the Contact thrust in the very southern part of the mapped area.

Wilson Cliffs-Contact thrust plate

The thrust plate that lies above the Jurassic Aztec Sandstone and below the Keystone thrust plate, as mapped during this study, can be divided conveniently into a northern and a southern segment divided by the Cottonwood fault (Fig. 6). The segment south of the fault is the Contact thrust plate mapped by Hewett (1931, 1956), Cameron (1977), Carr (1983), and Carr and Pinkston (1987). The segment north of the Cottonwood fault here is referred to as the Wilson Cliffs plate. Our mapping will demonstrate that the Contact and Wilson Cliffs plates are the same, but it is convenient to refer to them separately until all the evidence is presented.

Wilson Cliffs plate. The Wilson Cliffs plate can be traced from the Cottonwood fault 9 km north to where it is truncated by the Keystone thrust (Fig. 6). Before it ends, the Wilson Cliffs plate consists of a thin sequence of white dolomite (probably part of the uppermost Papoose Lake Member of the Bonanza King Formation) overlying thin slices of footwall rocks, and overlain by a conglomerate of post-Wilson Cliffs and pre-Keystone age (Figs. 6 and 8; see below). Southward, the plate contains a complex imbricate structure formed within rocks of the Banded Mountain Member and, more rarely, by rocks of the uppermost Papoose Lake Member of the Bonanza King Formation to the Nopah Formation (Fig. 6).

The Wilson Cliffs plate consists of numerous imbricate slices, and the fault at the base of the plate is a compound fault because it consists of fault segments that bound the base of different thrust imbricates. Figure 6 clearly shows the anastomosing faults that bound and imbricate the base of the plate. Where units are truncated or repeated by thrust faults they are easy to map; however, along strike, some of these faults enter a single map unit, often parallel to bedding, and cannot be traced further (if in fact they exist at all beyond that point). The thrust surfaces usually are sharp planar breaks with little or no breccia. However, the fault at the base of the plate commonly has breccia up to 5 m thick in its hanging wall. The thrust fault at the base of the plate dips from 8° to 20° west, steepening to 30° locally in western re-entrants (Fig. 6). Thrust faults within the plate commonly dip more steeply, and locally may dip from 60° to 75°; some thrust faults are folded (Fig. 9).

Eastward-overturned folds with subhorizontal axes are common within the imbricates of

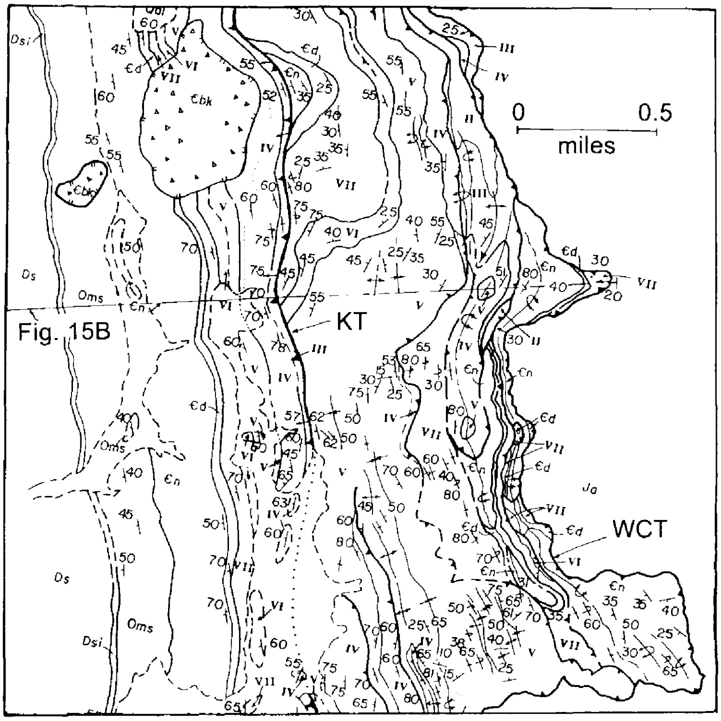

FIG. 9. Detailed geological map in the central part of the Wilson Cliffs (see Figure 6 for location). This area shows the contrast in style between the Wilson Cliffs and Keystone plates. The Keystone plate generally is a homoclinal slab, whereas the Wilson Cliffs plate consists of imbricate thrust slices, folded thrust faults, and upright and E-vergent folds. The nested folded thrust slices in the eastern part of the Wilson Cliffs plate are shown in Figure 10. The dotted line is the key unit traced in Unit V. Banded Mountain units are shown by roman numerals. Other units: Єd = Dunderberg Shale; Єn= upper Nopah Formation; Oms = Mountain Springs Formation; Dsi = Ironside Member of the Sultan Limestone; Ds = Sultan Limestone; Ja = Aztec Sandstone. Brecciated landslide masses are depicted by open triangles. Thrusts: KT = Keystone thrust; WCT = Wilson Cliffs thrust. The location of the cross section in Figure 15B is shown.

the Wilson Cliffs plate. Some synclines lie below thrust faults as footwall synclines, but corresponding hanging wall anticlines are rare (Fig. 10). In some places, E-vergent anticlines lie below thrust faults. More open folds with subvertical axial surfaces also are present. All fold axes trend generally NNW in the northern half of the plate, and north or NNE in the southern half. Some fold axes are curvilinear. Locally, E-trending folds are present. Most thrust surfaces are planar and fold axial surfaces parallel them or are truncated by them, except in one area. In the east-central part of the plate, two thrust faults are folded by E-vergent overturned folds (Figs. 9 and 10).

In the southern 3 to 4 km of the Wilson Cliffs plate, the structure is somewhat simpler. Its eastern part consists of a broad open anticline in the south and generally gentle W- or S-dipping strata farther north within Units V, VI, and VII of the Banded Mountain Member (Figs. 6 and 11). Imbricates are present, but generally are discontinuous. Its western part consists of tight folds, some overturned eastward, with W-dipping axial surfaces and segments of imbricate faults.

Contact thrust plate. The Contact plate is juxtaposed against the Wilson Cliffs plate and its footwall rocks across the Cottonwood fault (Figs. 6 and 11). The Contact plate carries rocks from the Bonanza King Formation to the Pennsylvanian–Permian Bird Spring Formation thrust eastward over the Aztec Sandstone (Fig. 6). Because the Contact thrust fault lies 3 km east of the Wilson Cliffs thrust fault south of the Cottonwood fault, and because the thrust

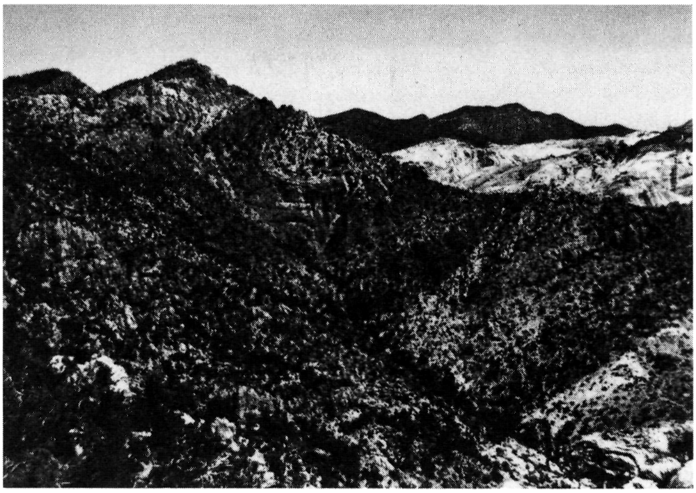

FIG. 10. View looking north at folded nested thrust faults in the eastern part of the Wilson Cliffs plate (folded Units IV and V in the eastern part of Figure 9). Wilson Cliffs thrust fault is the dark-white contact at the right of the photo. The prominent E-vergent syncline in the upper part of the ridge folds a thrust slice of Units IV (dark) and V (white) into Cambrian Nopah Formation (white on skyline). Other overturned folds are present on the ridge below.

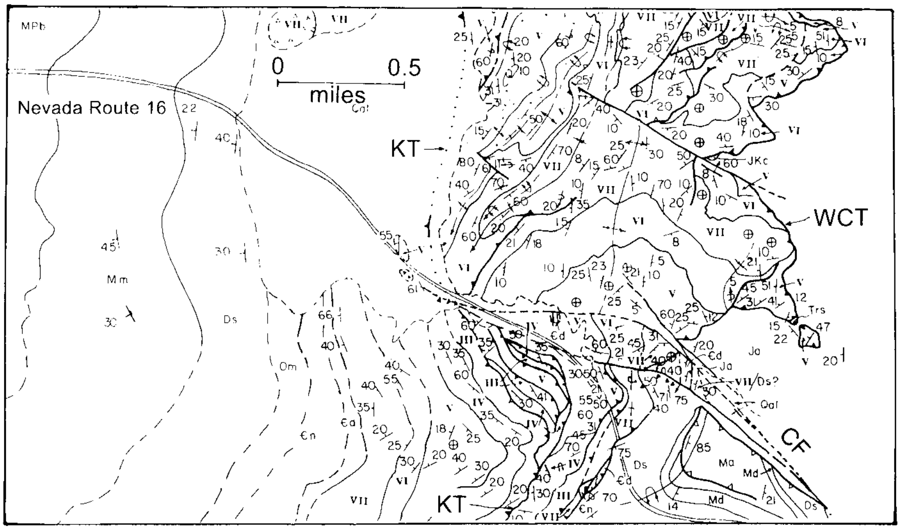

FIG. 11. Detailed geological map of the Mountain Springs Pass area (see Fig. 6 for location). This area contains the critical relations between the Wilson Cliffs (WCT) and Keystone (KT) thrust plates across the Cottonwood fault (CF). Units in the Banded Mountain Member are shown by roman numerals. Other units: Ꞓd = Dunderberg Shale; Ꞓn= upper Nopah Formation; Oms = Mountain Springs Formation; Ds = Sultan Limestone; Mm = Monte Cristo Limestone (locally subdivided into Ma = Anchor Limestone, Md = Dawn Limestone); Mpb = Bird Spring Formation; Trs = Shinarump Conglomerate; Jkc = channel conglomerate beneath the Wilson Cliffs thrust; Ja = Aztec Sandstone. Brecciated landslide masses are shown with open triangles. Silicified breccia along the Cottonwood fault is shown with solid triangles. Some of the key beds mapped are shown by dotted lines.

plate contains younger Paleozoic rocks than does the Wilson Cliffs plate, separation on the Cottonwood fault is south-side-down.

The structure of the Contact plate is somewhat different from that of the Wilson Cliffs plate. A frontal overturned anticline that has a

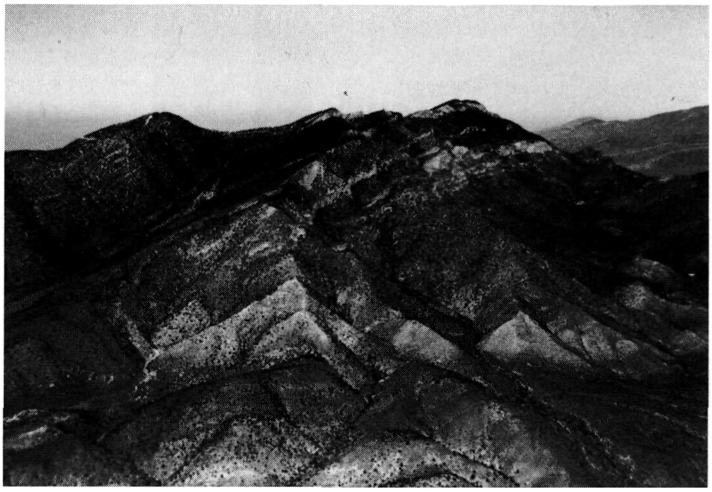

FIG. 12. View looking northwestward along the E-vergent frontal anticline of the Contact thrust plate. The S-plunging anticline is outlined in the center of the photo by the prominent light-colored beds of the Monte Cristo Limestone.

FIG. 13. View looking northward along the E-vergent Potosi syncline. Here the syncline is entirely within banded limestones of the Bird Spring Formation.

40° W-dipping axial surface is present in the eastern part of the plate (Figs. 6, 12, and 15C). The plunge of the fold axis varies from 8°S4–16°E in its northern part to 24°S 22–43°W in its southern part. A N-trending eastward overturned syncline, the Potosi Mine syncline, is present in the western part of the plate (Fig. 13). The syncline dies out to the north and downsection. The Potosi thrust fault, in the central part of the plate, dips 20° to 22° west. It cuts upsection to the east in both its hanging wall and footwall, and small folds associated with the thrust suggest an eastward direction of movement.

The frontal anticline, and the Potosi and Contact thrust faults, are displaced by the NNW-trending Ninety-Nine fault zone (Fig. 6). The fault zone, however, does not offset the Keystone thrust; the fault zone consists of several strands, and separation across the fault zone is north-side-down. Piercing points on both sides of the Ninety-Nine fault zone can be established by using the axis of the frontal anticline within beds of the basal Mississippian rock units. Because the piercing points must be projected onto the fault plane, they have a range of possible positions. Offsets of the extreme positions of the piercing points yield oblique-slip, a north-side-down component of 739 to 968 m, and a right-slip component of 1490 to 1823 m.

Along the northwestern part of the plate, there are several imbricates of Cambrian rocks that rest above younger Paleozoic rocks (Fig. 6). These are interpreted to be derived from the Contact plate, but it is not clear whether some of these might be derived from the higher Keystone plate. The imbricates in the southwestern part of the map area clearly are part of the Contact plate because their boundary faults die out within Cambrian rocks of the Contact plate. Even though the structure of the Contact plate appears to be somewhat different from that of the Wilson Cliffs plate, relations across the Cottonwood fault indicate that they are the same plate.

Cottonwood fault

Previous workers have interpreted the fault here mapped as the Wilson Cliffs thrust to be continuous across, or displaced only a few tens of meters by, the Cottonwood fault (see: Secor, 1962; Longwell et al., 1965; Davis, 1973; Burchfiel et al., 1974). They regarded the Wilson Cliffs thrust fault to be the continuation of the Keystone thrust fault and correlated it to the faults that place Cambrian rocks above younger Paleozoic rocks to the south of the Cottonwood fault. Mapping of units within the Bonanza King Formation shows that the Cottonwood fault has several branches that cut all units and structures within the Contact and Wilson Cliffs plates, but generally warp only the higher Keystone thrust plate (Fig. 11).

At least three WNW- to NW-striking faults comprise the Cottonwood fault in the poorly exposed Paleozoic rocks near Nevada Route 16, east of Mountain Springs Pass. These faults dip from 60° to 75° south and are marked by several meters of breccia. Locally the breccia is silicified and forms prominent red- and white-weathering boulders. Rocks as young as the Nopah Formation are contained within faulted blocks; the very characteristic shale and edgewise-limestone conglomerate of the Dunderberg Shale Member are present at two locations. Unlike the parallel Ninety-Nine fault zone to the south, the Cottonwood fault has a north-side-up separation and has affected the Keystone thrust plate.

Structures are not continuous across the Cottonwood fault. The imbricate thrust slices that contain rocks of the Banded Mountain Member, and include locally the Nopah Formation, south of the fault are juxtaposed against a broad open anticline within Units V, VI, and VII of the Banded Mountain Member to the north of the fault (Fig. 11). The two eastern imbricate thrust slices and their basal thrust faults are folded into a N-plunging syncline adjacent to the Cottonwood fault on its southern side. The rocks and thrust faults are overturned and dip eastward adjacent to the fault. Southeastward, Devonian and Mississippian rocks of the Contact plate are juxtaposed against slivers of Banded Mountain Member and Nopah Formation (including the Dunderberg Shale Member) within the Cottonwood fault zone and Jurassic Aztec Sandstone in the footwall of the Wilson Cliffs plate on the northern side of the fault. Thus, the relations indicate a large displacement on the Cottonwood fault.

The relations across the Cottonwood fault support the interpretation that the Wilson Cliffs and Contact plates are the same plate. Devonian and Mississippian formations of the higher Keystone plate are continuous, and unbroken, across the projected western continuation of the Cottonwood fault (Figs. 6 and 11; see below), and both the Wilson Cliffs and Contact plates rest on the Jurassic Aztec Sandstone; thus the two plates have the same structural position. The overturning of structures along the southern side of the Cottonwood fault and the fault slivers of Cambrian rocks within the fault zone are best explained by a south-side-down (or left-slip) displacement or by an oblique-slip combination of the two displacements, again supporting the correlation of the two plates. Correlation of structures offset across the Cottonwood fault can be made as follows. Western imbricates and overturned folds are present in both plates. They lie west of the open anticline north of the fault, a location that corresponds to the gently folded, upright western limb of the recumbent fold in the Contact plate to the south (Fig. 6). The recumbent fold within the eastern part of the Contact plate would have been removed by erosion from the eastern part of the Wilson Cliffs plate. If these correlations are correct, the slip on the Cottonwood fault post-dated emplacement of the Contact–Wilson Cliffs plate.

Earlier interpretations suggested two periods of displacement on the Cottonwood fault, one following emplacement of the Contact thrust and preceding the emplacement of the Keystone thrust, and the second following emplacement of the Keystone plate (see Davis, 1973; Burchfiel et al., 1974). The magnitude and sense of slip were not treated in detail by earlier workers, who suggested only a south-side-down sense of displacement on the Cottonwood fault. Detailed mapping shows warping of the Keystone plate, and folding of the imbricates of the Contact plate might suggest that the Cottonwood fault also had a left-slip component.

Even with detailed mapping, the timing and magnitude of displacement across the Cottonwood fault are difficult to reconstruct. There is considerable difficulty in supporting left-slip movement on the Cottonwood fault. Piercing lines can be constructed from the intersection of Units V–VII with the Contact and Wilson Cliffs thrust faults. Units V–VII are exposed north of (and within) the Cottonwood fault zone (Fig. 11); however, the Contact thrust exposes only rocks as old as the Ordovician Mountain Springs Formation in the core of its frontal anticline ~0.5 mile (800 m) farther southeast on the southern side of the fault. Detailed cross sections indicate that Units V–VII would be present above the Contact thrust about one-quarter to one-half mile (400–800 m) west of the surface expression of the axial trace of the frontal anticline (see cross section in Figure 15C). This would place them almost directly south of the same units in the Cottonwood fault zone. Thus, the amount of left-slip on the fault would be only a few hundred meters at most and could be zero; this is insufficient to explain the 2.0- to 2.25-mile (3.2- to 3.6-km) left-separation of the Contact and Wilson Cliffs thrusts.

A single period of post-Keystone south-side-down displacement can explain all the mapped geological relations. Cross sections drawn across the Cottonwood fault indicate that the Contact thrust is ~3100 feet (940 m) lower on the southern side of the fault than is the Wilson Cliffs thrust on the northern side. The Wilson Cliffs thrust dips ~10 to 15° to the west. Assuming a 15° dip, a south-side-down displacement of ~3500 feet (1060 m) is necessary to cause a 2.0- to 2.25-mile (3.2- to 3.6-km) left-separation on the thrust. Warping of the Keystone thrust is more difficult to quantify, because exposures are poor in the area where it intersects the Cottonwood fault. The thrust front is shifted sinistrally about 3800 feet (1150 m) across the projected trend of the Cottonwood fault. The Keystone thrust dips more steeply than the Contact–Wilson Cliffs thrust. Assuming a dip of ~45° to the west, a south-side-down displacement on the Cottonwood fault of 3800 feet (1150 m) would accomplish the measured shift. Thus, on the basis of the crude measurements that can be made, it is possible that the present map patterns of the thrust faults could be accomplished by a single, post-Keystone, south-side-down displacement of ~3500 to 3800 feet (1060 to 1150 m). The displacement on the Cottonwood fault still must fade out into warping at, or just west of, its intersection with the Keystone thrust. Other, more complex, multistage displacements are possible, but the present data do not require them.

The Keystone plate

The structurally higher thrust plate, and its basal thrust fault, can be traced from the type area of the Keystone plate at the Keystone Mine (Fig. 1) (Hewett, 1931; Carr, 1983) northward into the higher thrust plate in the map area (Fig. 6); thus, the higher thrust plate is the Keystone plate. In contrast to the Wilson Cliffs–Contact thrust plate, the Keystone plate is structurally simple. Throughout most of the map area, and south to the Keystone Mine, it consists of a W-dipping panel of rocks ranging from the Banded Mountain Member of the Bonanza King Formation at the base to the Mississippian Monte Cristo Formation; westward beyond the map area, the sequence continues into the Triassic Moenkopi Formation. The Keystone thrust fault, and its hanging-wall stratigraphic units, can be traced continuously over the length of the map area. Only locally are they covered by older alluvial deposits and landslide masses of brecciated Bonanza King rocks in the south-central part of the area.

Where exposed, the thrust surface is a sharp break and is marked by little or no evidence of

FIG. 14. Unit I of the Banded Mountain Member of the Bonanza King Formation, lying less than 50 cm above the Keystone thrust. Very thin laminae and burrow mottling are preserved with no evidence of brecciation or proximity to a major thrust fault. This characteristic is common along the Keystone thrust and along many of the subsidiary thrust faults in the map area.

either brittle or ductile deformation (Fig. 14). The trace of the Keystone thrust fault trends generally N-S and is gently arcuate, except where it interacts with the Cottonwood fault at Mountain Springs Pass. The thrust fault is mostly parallel to bedding, dipping 30° to 40° in the northern and southern part of the area and 55° or 65° in the central part of the area. No rocks of the lower member of the Bonanza King Formation are present in its hanging wall over the entire map area. Cross sections indicate that the Keystone thrust truncates the Wilson Cliffs-Contact thrust fault at depth (Fig. 15). Only in the southern part of the map area does the Keystone plate contain a few E-vergent to upright folds and possible imbricates. Some of the imbricates below the Keystone thrust near the Cottonwood fault could be interpreted as derived from the Keystone plate. Otherwise, internal structure of the Keystone plate is a homoclinal slab shallowing in dip west of the map area.

Near the Cottonwood fault, the Keystone plate is folded in the same sense as the displacement of the Wilson Cliffs-Contact plate across the Cottonwood fault (Figs. 6 and 11). At Mountain Springs Pass, the intersection of the Keystone thrust and the Cottonwood fault is covered by alluvium, but Devonian and younger formations are continuous across the western projection of the Cottonwood fault, indicating that the Keystone plate is warped but not offset by movement on the Cottonwood fault. Warping of the Keystone plate must be at least partly post-Keystone in age. Earlier workers considered movement on the Cottonwood fault to be entirely pre-Keystone in age, whereas the evidence presented here suggests that it may be entirely post-Keystone in age.

No rocks older than the Banded Mountain Member of the Bonanza King Formation are present in the hanging wall of the Keystone thrust fault. Although there appears to be a stratigraphic control of the thrust fault, in detail the fault follows different units of the Banded Mountain Member along strike. The thrust fault lies within Units I to IV, transgressing them locally at a low angle except where the high-angle Griffith fault is truncated by the Keystone in the northern part of the area.

Age Relations of Structures within the Map Area

The oldest structure in the area is the Boundary fault in the southeasternmost part of the area. It is never exposed, but its presence is indicated by displaced Mesozoic rocks in the footwall of the Contact plate; Jurassic Aztec Sandstone to the north strikes into Triassic

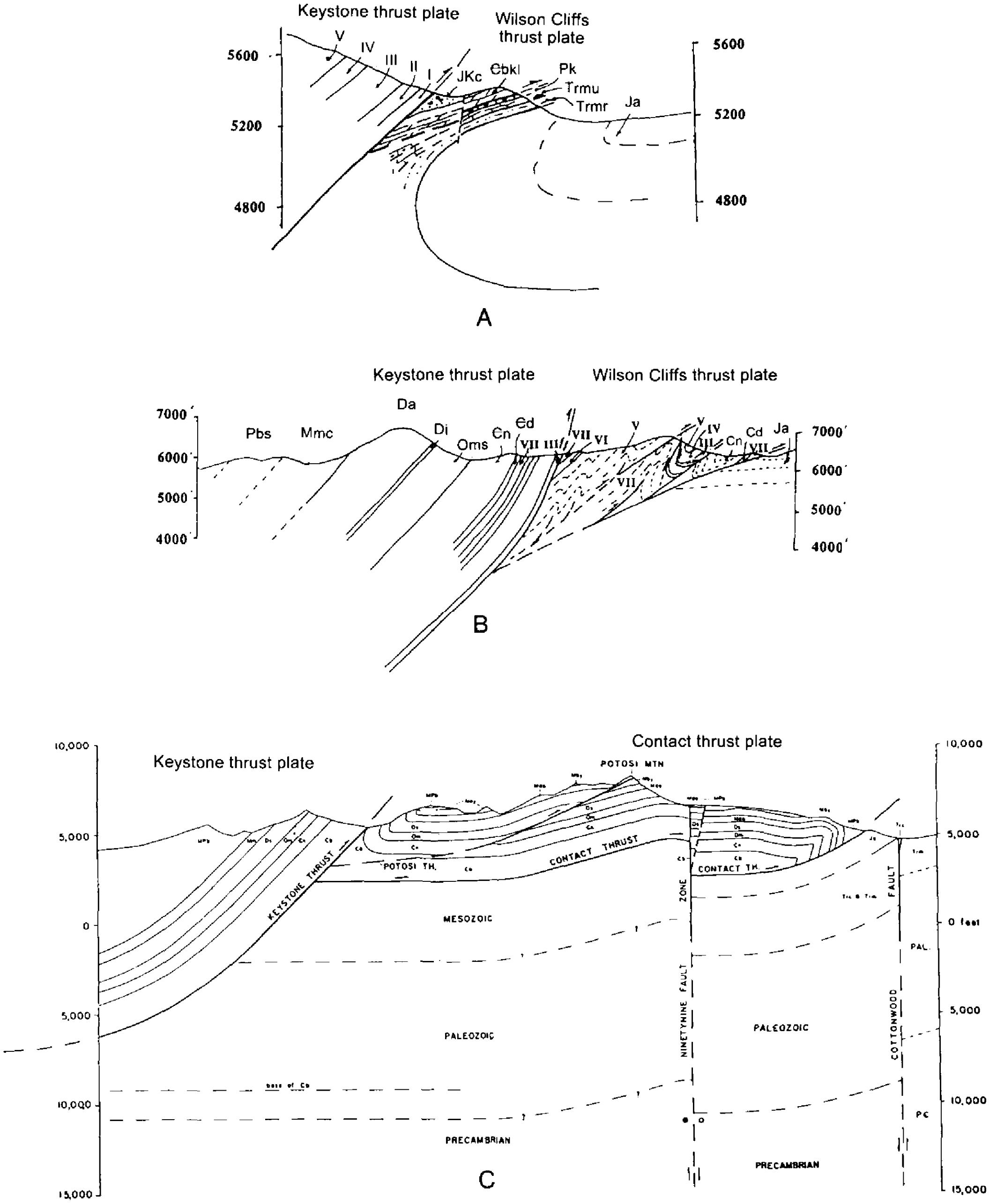

FIG. 15. Cross sections through the Wilson Cliffs area (no vertical exaggeration). Locations are shown in Figures 6, 8, and 9. Note that each cross section has a different scale. A. Section through the northern part of the area, showing that the Keystone thrust truncates the Wilson Cliffs thrust at depth. It also shows the relations between the JKc conglomerate and sandstone unit and the two thrust plates. The basal and eastern contacts of the JKc unit are not exposed in the field. B. Cross section through the middle part of the Wilson Cliffs area; location is shown on Figures 6 and 9. This cross section depicts the difference in structural style between the strongly folded and imbricated Wilson Cliffs plate and the slab-like character of the Keystone plate. Figure 10 shows the folded thrust in the eastern part of the section. C. Cross section through the Potosi Mountain area in the southern part of the map area, showing the truncation of the Contact thrust by the younger Keystone thrust.

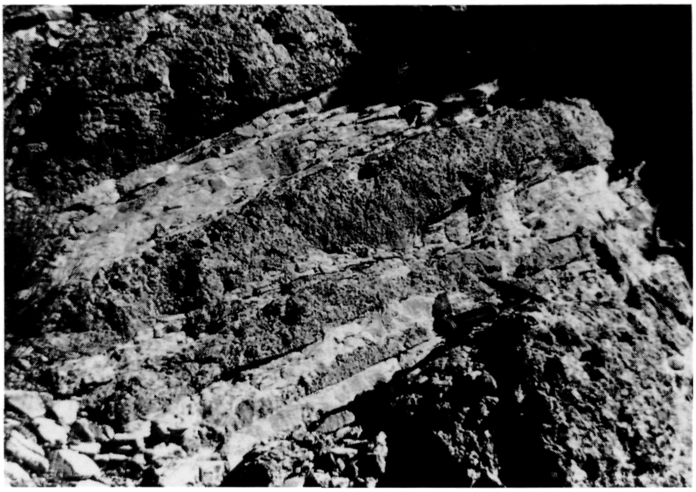

FIG. 16. Close-up of the JKc sandstone and conglomerate unit that lies below the Keystone thrust in the northern part of the area (see also Figs. 8 and 15A). White beds are quartz sandstone reworked from the Aztec Sandstone; dark beds are conglomerate consisting only of clasts of Bonanza King Formation with quartz sand matrix.

rocks to the south (Fig. 6). The fault does not displace the Contact thrust.

The next oldest structures in the area are the result of eastward emplacement of the Contact thrust plate. The Potosi thrust in the southern part of the area probably is related to movement of the Contact plate, because it is intimately related to major folds in the Contact plate, whose geometric relation to the thrust fault indicates that their formation is part of the emplacement process. The Potosi syncline in the southwestern part of the area also was formed during the emplacement of the Contact thrust plate, because its axial surface and axial plunge are similar to those of the frontal eastward overturned anticline in the Contact plate. The Potosi syncline is older than the Keystone thrust because its axial trace is truncated by the Keystone thrust (Fig. 6) and small folds on its overturned limb are refolded by folds related to emplacement of the Keystone plate (see also Carr, 1983).

The Ninety-Nine fault zone also is older than the Keystone thrust, but probably is younger than the emplacement of the Contact plate. It displaces the Potosi thrust by normal-right oblique slip (see above), but cannot be considered a tear fault in the contact plate because right-lateral displacement on this NW-trending fault is the wrong sense for a tear fault in the E-vergent Contact plate. Thus, it is younger than the emplacement of the Contact plate. Although its western continuation is covered by alluvium and landslide material, the Ninety-Nine fault zone does not offset the Keystone thrust; thus it is older than the emplacement of the Keystone plate (Fig. 6).

All evidence indicates that emplacement of the Keystone plate is younger than emplacement of the Contact plate. Cross sections (Fig. 15) indicate (as do the mapped relations at the northern end of the area) that the Keystone thrust fault truncates the Wilson Cliffs–Contact thrust fault at depth. The ramp for the Keystone thrust, therefore, lay east of the ramp for the lower Wilson Cliffs–Contact plate. Thus, the Wilson Cliffs–Contact plate cannot be simply a slightly older and more easterly part of the Keystone. At the northern end of the map area, about 2 miles (3.2 km) south of Willow Spring, sandstones and conglomerates are in fault contact below the Keystone thrust (Figs. 8 [labeled Jkc], 15A, and 16). These rocks consist of 15 to 20 m of gently W-dipping sandstone composed of reworked Aztec Sandstone interbedded with boulder and cobble conglomerate (Fig. 16). The cobbles consist of Bonanza King dolomite and limestone set in a matrix of reworked Aztec Sandstone. Cross-bedding indicates that the sand was derived from the east, suggesting that the rocks are not a synorogenic deposit derived from an advancing Keystone plate, but are erosional products from the Wilson Cliffs plate.

We interpret these rocks to have been deposited unconformably on the Wilson Cliffs plate following a period of erosion between the emplacement of the Wilson Cliffs–Contact plate and the Keystone plate. Unfortunately, the basal and eastern contacts of the conglomerate and sandstone unit are not exposed along its 100- to 200-m outcrop length. Except for being cut by the Keystone thrust at the top, the conglomerate and sandstone unit is undeformed and right-side-up, in contrast to the overturned and highly brecciated rocks beneath it. This suggests that the unit was deposited after emplacement and considerable erosion of the Wilson Cliffs plate. In fact, we suggest that the northern termination of the Wilson Cliffs plate occurred principally through erosion before the Keystone plate was emplaced. This interpretation suggests that a considerable period of time separated the emplacement of the Wilson Cliffs–Contact and Keystone thrust plates, and it is consistent with regional tectonic relations discussed below.

Very small deposits of conglomerate are present in two other locations resting unconformably on the Wilson Cliffs plate, but are too small to appear in Figure 6.[3] Both deposits are fault bounded on at least one side, but nowhere are they in contact with the Keystone plate. Thus, their correlation with structural events is unknown, except that they were deposited after emplacement of the Wilson Cliffs plate. They represent remnants of the deposits discussed above, because the more northerly of the two deposits contains reworked Aztec Sandstone. Dating of the emplacement of the two plates, however, cannot be determined in the map area and must be ascertained from regional relations.

Without additional constraints, a single, south-side-down displacement on the Cottonwood fault is all that is required to explain the mapped geological relations across the fault. This displacement would be younger than emplacement of the Keystone thrust. Mapping in progress in the Bird Spring Range to the southeast is focused partly on the unresolved question of the history of, and displacement on, the Cottonwood fault.

The nearly vertical Griffith fault in the northern part of the map area offsets map units in the hanging wall of the Keystone plate, but does not offset the Keystone thrust (Figs. 6 and 8). Where the two faults intersect there is a broad area of brecciated rocks, and the Griffith fault curves south to merge with the Keystone thrust. The Griffith fault could be interpreted as a tear fault in the Keystone plate, or as a younger fault that merged with the Keystone thrust, reactivating it. Not enough of the Griffith fault was mapped during this study to resolve the interpretation.

Regional Tectonic Relations

The major difference between this study and earlier studies is the interpretation that the spectacularly exposed thrust fault at the top of the Wilson Cliffs, referred to by previous workers as the Keystone thrust, is not the Keystone thrust, but is the basal fault of an older thrust plate (Fig. 17A). In addition, previous workers interpreted the Cottonwood fault to be one of several demonstrable pre-Keystone NW-trending faults (Fig. 17B). Davis (1973), as well as Burchfiel et al. (1974), suggested that the oldest structural event in the area was the emplacement of the Contact thrust plate and its northern correlative, the Red Spring plate. Younger, high-angle faults, such as the La Madre and Cottonwood faults, displaced and locally rotated the Contact–Red Spring thrust plate. At least one of these high-angle faults, the Ninety-Nine fault zone, has a component of strike-slip. Extensive erosion ensued and removed the once-continuous Contact–Red Spring plate from the horst between the Cottonwood and La Madre faults. The Keystone thrust plate was emplaced across an erosion surface in its eastern part that is now exposed in the mapped area (Fig. 17B).

The sequence of events determined from this study modifies two parts of the events described above: (1) the Contact–Red Spring thrust plate was not entirely removed by erosion from the horst between the Cottonwood and La Madre faults, as a remnant of that plate remains as the Wilson Cliffs plate; and (2) the displacement

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[3] These are shown on the detailed geologic map of the area available elsewhere; see note 1.

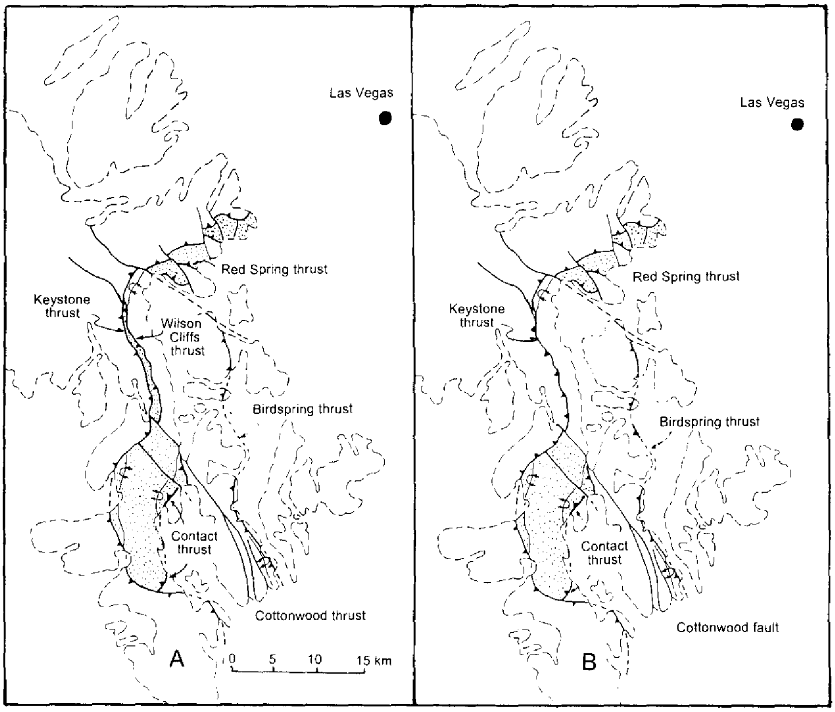

FIG. 17. Previous (B) and present (A) interpretations of the tectonic relations between the Keystone and structurally lower thrust plates in the eastern Spring Mountains.

on the Cottonwood Fault is mostly, if not entirely, post-Keystone in age (Fig. 17A). Mapped relations indicate that the Wilson Cliffs plate is the lateral continuation of the Contact plate and probably also of the Red Spring plate. The conglomerate deposits at the northern end of the map area are interpreted to represent one of the few places where rocks deposited during the post-Wilson Cliffs and pre-Keystone erosion interval are preserved.

Dating of these events remains uncertain, and there is no evidence within the map area to bound these deformations other than to assign them a post-Aztec Sandstone, pre-Quaternary age. Recent work by Fleck et al. (1994) has indicated that the Keystone plate was emplaced probably between 100 and 83 Ma. Emplacement of the Contact-Wilson Cliffs-Red Spring plate and movement on the high-angle faults that displace it were earlier, but how much earlier remains unknown.

Some or all of the movement on both the Cottonwood and Griffith faults could have occurred after emplacement of the Keystone thrust plate. It is possibile that some or all of the movement on these two faults is Cenozoic in age. The NW-striking Las Vegas shear zone is a Late Cenozoic transfer fault that accommodates Basin and Range extension (Liggett and Childs, 1974; Wernicke et al., 1982); these two faults have the same strike and could have formed at the same time. Recent mapping in the Bird Spring Range along the southeastern continuation of the Cottonwood fault shows that this fault displaces boulder conglomerate of undated, but probable Cenozoic, age (K. V. Hodges, pers. commun., 1996). If these faults do have a Cenozoic history, there may be a greater imprint of Cenozoic deformation on this area than previously thought.

Conclusions

Results of this study are relevant to local and regional structural interpretations and to considerations of the mechanics of thrust faulting. Locally, detailed mapping demonstrates the presence of two thrust plates in the Wilson

Cliffs–Potosi Mountain area—the lower Wilson Cliffs plate, a remnant of a once more extensive Contact–Red Spring thrust plate, and the higher Keystone thrust plate. The thrust fault so magnificently exposed atop the Wilson Cliffs is not the Keystone thrust, but a part of the structurally lower and older Contact–Wilson Cliffs–Red Spring thrust fault.

The emplacement of the Keystone and Contact–Wilson Cliffs–Red Spring thrust plates belongs to two different thrusting events that are separated by a period of high-angle faulting and erosion. The Cottonwood fault, previously interpreted to be one of these high-angle faults, probably experienced most or all of its displacement after emplacement of the Keystone plate. The Contact–Wilson Cliffs–Red Spring thrust plate lies east of and structurally below the younger Keystone plate. However, because the ramp for the Keystone thrust lies east of the Contact–Wilson Cliffs–Red Spring thrust, there was eastward progression of the younger thrust at a low structural level. But the Keystone thrust cut across the Contact–Wilson Cliffs plate at a high structural level so that its present erosional trace lies west of the trace of the Contact–Wilson Cliffs thrust, and the present map pattern gives an erroneous impression. Work in progress in the Bird Spring Range suggests that the Bird Spring thrust (Fig. 1) is older than the Keystone thrust, thus supporting: (1) the concept that a more easterly thrust is older than the Keystone thrust (i.e., the Keystone thrust is "out of sequence" with respect to the Bird Spring thrust, but not with respect to the Contact–Wilson Cliffs thrust); and (2) similar conclusions of other studies of the thrust faults farther south by Burchfiel and Davis (1971, 1981, 1988) and Carr (1983).

Geometric relations suggest that the ramp for the Keystone plate lay east of the ramp for the Contact–Wilson Cliffs–Red Spring plate (Fig. 15A); thus the Keystone plate must have carried parts of both the hanging wall and footwall of the Contact–Wilson Cliffs–Red Spring plate in its eastern part as well as the high-angle faults that cut them. These parts of the Keystone plate must have been removed by erosion, as they are not exposed. Furthermore, the Keystone plate of the map area detached within a narrow stratigraphic interval that was not affected by older high-angle faults. These relations suggest that the Keystone plate was displaced eastward relative to its footwall by a considerable (but unknown) distance, a suggestion supported by differences in Cambrian stratigraphic units (particularly Unit VII and the Nopah Formation) in its hanging wall and footwall.

After ramping up-section, both thrust plates moved across erosion surfaces. Below the Contact–Wilson Cliffs–Red Spring plate, this erosion surface was developed on the Jurassic Aztec Sandstone; below the Keystone plate, however, the erosion surface was developed across highly varied and complex geology.

Even though the two thrust plates are of different ages, they both detached at about the same stratigraphic interval within the Bonanza King Formation. Detachment occurred within an interval of ~100 m between the uppermost part of the Papoose Lake Member and Unit IV of the Banded Mountain Member. Reasons for a detachment in this interval are not obvious, particularly when the Bright Angel Shales almost certainly lay only 100 to 200 m lower stratigraphically. The boundary between the two members of the Bonanza King Formation marks a change from rocks that are predominantly limestone below to predominantly dolomite above. However, the detachment does not follow this lithological change precisely, but for the most part stays within that part of the sequence dominated by dolomite. New interpretations for the Cottonwood and Griffith faults suggest that Cenozoic deformation was more important in the eastern Spring Mountains than previously recognized.

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