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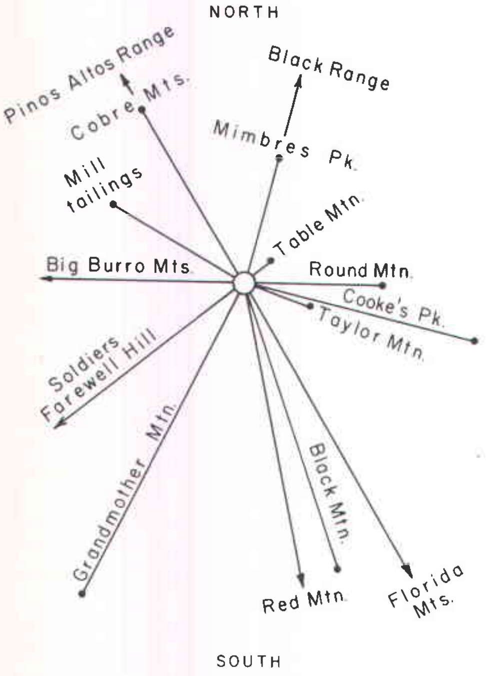
Correction

In the February 1980 issue of *New Mexico Geology,* the panoramic diagram to accompany the City of Rocks article was omitted. That diagram is printed below.



Call for papers

The Rocky Mountain Section of the American Association of Petroleum Geologists will meet in Albuquerque April 12-15, 1981, at the Hilton Inn. Thomas E. Kelley of Geohydrology Associates, Inc., is General Chairman of the conference. Papers on Rocky Mountain regions are welcome; contact Lee Woodward, University of New Mexico, or Frank Kottlowski, New Mexico Bureau of Mines and Mineral Resources, Program Chairman, at your earliest convenience. ☐

Proterozoic tectonic setting in New Mexico

by Kent C. Condie, Department of Geoscience, New Mexico Institute of Mining and Technology, Socorro, NM

Geological features

Recent detailed mapping of Proterozoic terranes in New Mexico has enhanced our understanding of stratigraphy and tectonic setting. Chief areas of investigation (fig. 1) are Precambrian exposures in the south and south-central part of the state (Condie and Budding, 1979) and the Sangre de Cristo Mountains in the northern part of the state (Robertson and Moench, 1979; Barrett and Kirschner, 1979; Woodward and others, 1979; Nielsen and Scott, 1979; Condie, 1979).

Diagrammatic cross sections for the Proterozoic rocks in the Manzano and Ladron Mountains in central New Mexico are shown in fig. 2. The Manzano succession is characterized by a lower sequence of mixed arkose, quartzite, and subgraywacke, whose base is not exposed. This sequence is unconformably overlain by a thick succession of shales (now phyllites) with quartzite and arkose beds. The youngest rocks are bimodal volcanics whose felsic component dominates. The entire succession is folded into an overturned syncline and intruded with syntectonic to posttectonic granitic rocks. Unlike the Manzano succession, the Ladron succession is characterized by a lower bimodal volcanic sequence whose base is also concealed (Condie, 1976b). These volcanics are gently folded and intruded by the posttectonic Capirote granite. Unconformably overlying the granite is a succession of arkoses, quartzites, and conglomerates with minor shale and bimodal volcanics. This sequence is gently folded and cut by faults, and the entire Ladron succession (including the Capirote granite) is intruded by the posttectonic Ladron quartz monzonite.

Other supracrustal successions in New Mexico and southeastern Arizona show similar rock types and relationships to granites. All are characterized by bimodal volcanics with an absence or sparsity of volcanic or plutonic rocks of intermediate composition. Deformational features reflect chiefly vertical forces. Ophiolites, mélanges, blueschists, graywackes, and deep-sea sediments are absent.

Primary structures in the form of crossbedding, various sole markings, and ripple marks preserved in some of the clastic sediments are being investigated. Festoon crossbedding dominates in the arkoses and conglomerates; planar crossbedding dominates in the pure quartzites. Existing data seem to favor a near-shore, perhaps partly fluvial, environment of sedimentation for the coarse clastic sediments, with the shales being deposited in deeper, quiescent basins. Provenance studies (Condie and Budding, 1979) indicate source areas composed chiefly of high-K granites and reworked supracrustal rocks. No evidence exists for an older tonalitic source.

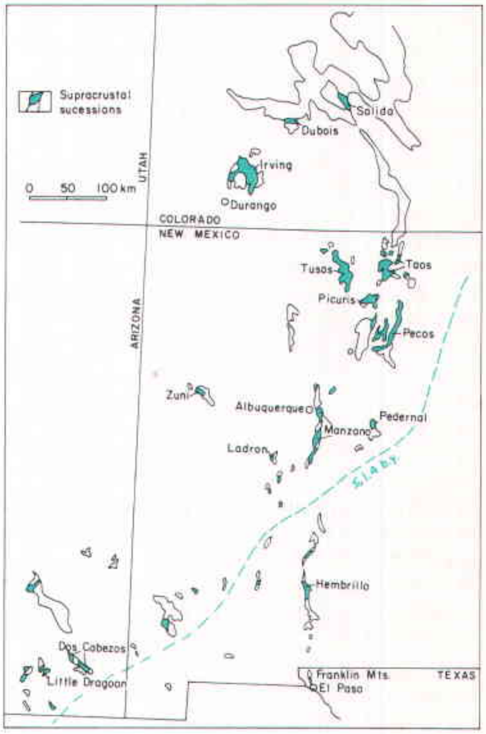


FIGURE 1—Distribution of Proterozoic rocks in New Mexico, southern Colorado, and southeastern Arizona.

Geochemical and Sr isotope studies

Geochemical studies of mafic and felsic volcanics and of granitic rocks have been important in determining magma origin and source composition (Condie, 1978a, b; Condie and Budding, 1979). Mafic volcanic rocks are tholeiites that range from depleted to undepleted in light REE (rare-earth elements). Geochemical model studies indicate that these rocks can be produced by 20-40 percent partial melting of a lherzolite source in the mantle followed by up to 30 percent olivine crystallization. REE distributions do not allow residual garnet, amphibole, or plagioclase in the source. Tholeiites depleted in REE occur only in the Pecos and Tijeras greenstones in central and northern New Mexico. Model studies indicate that these rocks were derived from depleted mantle sources similar to the sources of modern mid-ocean-ridge tholeiites. The absence of ophiolites in the supracrustal successions suggests that, although depleted mantle was tapped, oceanic crust was not formed.

Geochemical model studies of felsic volcanics and granitic rocks indicate an origin by partial melting of lower crustal rocks (granulite facies) for granodiorites and rhyodacites (Condie, 1978b). The high-K granites and rhyolites seem to have a similar origin followed by fractional crystallization. Initial Sr^{87}/Sr^{86} ratios in granitic and felsic volcanic rocks vary with age. Low ratios (0.701–0.703) characterize the group dated from 1.75 to 1.65 b.y. and high ratios (0.705 or greater), the group dated from 1.5 to 1.3 b.y. Low initial ratios in the older group reflect a mantle source; high ratios in the younger group reflect either a significant crustal residence time (approximately 300 m.y. or more) and/or contamination with radiogenic Sr.

Proterozoic tectonic settings

CURRENT THEORIES—One of the major problems in geology is the role of plate tectonics in the evolution of the Precambrian crust. Although many methods (geometric fit of continents, history of sea-floor spreading, and matching stratigraphy and crustal provinces) of identifying plate boundaries and reconstructing plate motions can be applied to events of the last 200 m.y., few apply to older geologic terranes. Two theories deal with the role of plate tectonics during Precambrian time. The strictly uniformitarian theory (Burke and others, 1977) suggests that plate-tectonic processes have always operated (at least since 2.7 b.y.), while the non-uniformitarian theory maintains that plate tectonics began about 1 b.y. ago or was manifest in a different manner before then (Engel and Kelm, 1972; Wynne-Edwards, 1976). Paleomagnetic data suggest that the present continents were part of one or perhaps a few supercontinents prior to 1 b.y. (Piper, 1976). If Phanerozoic-type plate tectonics were operating, the maximum size of new ocean basins allowed within a supercontinent would be 1,000 km or less and individual cratons would be allowed to rotate independently of each other only 10–20 degrees. Geological and geochronological evidence from Africa does not support a convergent-plate-boundary origin for Precambrian mobile belts (Kroner, 1977). Evidence favors an ensialic origin for African mobile belts prior to 1 b.y. although some investigators still interpret these mobile belts as continent-continent collision boundaries (Burke and others, 1977).

Modern plate regimes are characterized by specific rock associations and structural histories which, when found in older terranes, help interpretation of tectonic setting. In terms of rock associations, divergent-plate boundaries are commonly characterized by ophiolites (ultramafic rocks successively overlain by layered gabbro, sheeted diabase dikes, and pillowed basalts); convergent-plate boundaries by arc associations (calc-alkaline volcanics and batholiths, graywackes, and others); continental rifts by bimodal volcanics, arkoses, and conglomerates; and stable cratons and trailing continental edges by mature sedimentary successions (shale, carbonate, quartzite) and minor mafic volcanics (Condie, 1976a).

In terms of structural history, divergent-plate-boundary and continental-rift associations are characterized by normal faulting and gravity slump features; convergent boundaries and collision boundaries by strong compressional features; and stable-craton–trailing-edge associations by little if any contemporary deformation. Continental collision boundaries such as sutures are generally thought to be characterized by shear zones and mélange that contains exotic blocks of ophiolite, arc successions, blueschists, and deep-sea sediments. Ancient suture zones, however, are difficult to recognize because of complex plate histories or deeper level of exposure in the crust. Recently, diverse geological evidence has been used to identify Precambrian sutures, and many geologists are not sure that sutures can be accurately identified when they do not fall within the framework of the original definition.

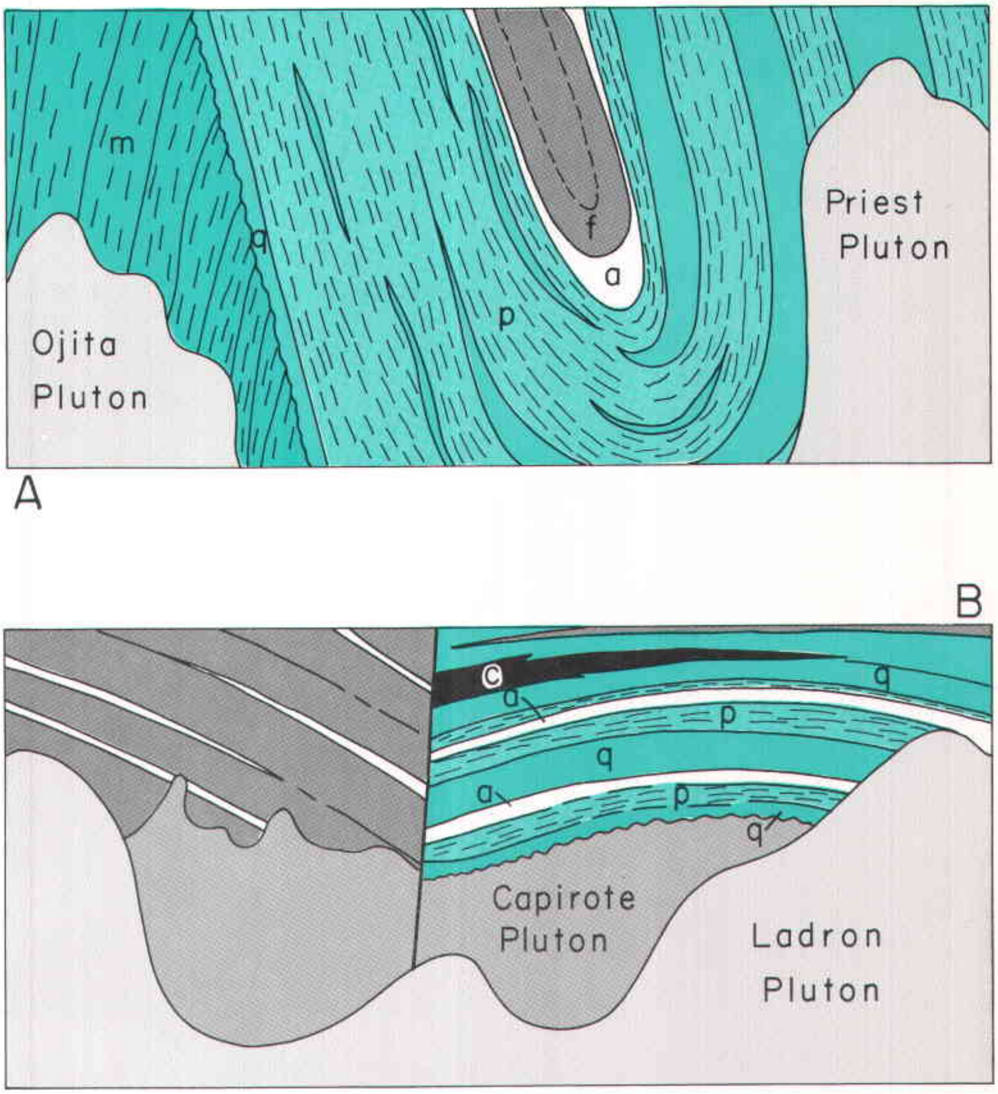


FIGURE 2—DIAGRAMMATIC CROSS SECTIONS OF PROTEROZOIC ROCKS (**m**, mixed clastic sediments; **q**, quartzite and arkose; **p**, pelitic sediments; **f**, felsic volcanics; **a**, mafic volcanics; **c**, conglomerates). **A**, Manzano Mountains; **B**, Ladron Mountains (after Condie, 1976b).

Distinctive ophiolite, arc, continental-rift, and stable-craton successions have been identified in some Proterozoic terranes. The oldest well-described ophiolites occur in Pan-African mobile belts (LeBlanc, 1976). Examples of arc successions are the 1.8-b.y. Coronation geosyncline (Hoffman, 1973) and the lower part of the 1.3-b.y. Grenville Supergroup (Condie and Moore, 1977), both in Canada. A convergent-plate-boundary model has also been proposed for the Svecofennian (1.8 b.y.) in Finland (Hietanen, 1975). The oldest known stable-craton succession is the Kaapvaal Basin in South Africa. One of the oldest known continental rifts is the Keweenawan (about 1 b.y.) in the Lake Superior area. Some Proterozoic supracrustal successions, however, do not readily fit into a plate-tectonic model. The Labrador geosyncline and the Cape Smith fold belt in Canada have been interpreted in plate-tectonic and other structural frameworks.

Early to middle Proterozoic (2.5–1.0 b.y.) supracrustal successions seem to occur in distinct geographic provinces. Many greenstone belts in the Churchill Province in Canada are Proterozoic (Moore, 1977). Proterozoic successions with well-preserved primary textures and structures also occur in peninsular India (Pichamuthu, 1975), in the Birrimian in West Africa (Burke and Dewey, 1972), and in the southwest United States.

RESULTS FROM THE SOUTHWEST—Major Proterozoic supracrustal belts in New Mexico and adjacent areas of Colorado and southeastern Arizona are shown in fig. 1; Precambrian rocks in this region range in age from about 1.8 to 1.0 b.y. (Condie and Budding, 1979). Detailed U-Pb zircon studies (Anderson and Silver, 1976) suggest two cycles of Proterozoic volcanism-sedimentation in Arizona, each followed by deformation, metamorphism, and plutonism. The earliest cycle (1.82–1.72 b.y., in central Arizona) probably extends into Colorado and northern New Mexico (Barker and others, 1976). The second cycle (1.72–1.66 b.y., in southeastern Arizona) probably extends into central and northern New Mexico. Isotopic evidence for Archean basement has not been found in the Southwest. Existing Sr-isotope data suggest that if the supracrustal volcanics were erupted and deposited on sialic basement, such basement must be less than 200 m.y. older than the volcanism (Condie and Budding, 1979).

Existing data on lithologies in the Proterozoic supracrustal belts in the Southwest indicate a diversity of rock types. Successions (fig. 1) are characterized by quartzite, shale, arkose, and bimodal (mafic and felsic) volcanic components; most successions in central Arizona are characterized by calc-alkaline volcanic and graywacke suites. The surrounding plutonic rocks in all areas are dominantly granodiorite and quartz monzonite intruded into supracrustal successions. Basement for the supracrustals has not yet been found. Metamorphic grade ranges from lower greenschist facies to upper amphibolite facies.

TOWARDS A TECTONIC MODEL—Opinions vary regarding the tectonic setting of this region during the Proterozoic. Based on fragmentary geochemical evidence from several trondhjemites, Barker and others (1976) have suggested that a northerly dipping subduction zone may have existed beneath Colorado and northern New Mexico at approximately 1.8 b.y. On the other hand, Hills and others (1975) have suggested a southerly dipping subduction zone beneath Colorado, based on lithologic assemblages. Hills and others further suggest the closing of a marginal-sea basin and suturing of Proterozoic crust against Archean crust along the Nash Fork–Mullen Creek shear zone exposed in southeast Wyoming. Silver and others (1977) propose a "magmatic arc" model for the Proterozoic of the Southwest; Anderson and Silver (1976) have likened the Jerome–Prescott supracrustal belt to an Archean greenstone belt. The absence of evidence for oceanic crust (ophiolites), volcanic arcs (andesites, graywackes, and blueschists), or sutures (shear zones and mélange) in the Proterozoic of New Mexico and adjacent regions in Colorado and southeastern Arizona does not favor the existence of a convergent-plate-boundary in this region during this time. Existing data are, however, consistent with a continental rift system in this area from 1.75 to 1.65 b.y. (Condie and Budding, 1979). The number and orientation of rifts and the nature and age of the continental crust upon which such a rift system may have developed are problems being addressed by current research.

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Pleistocene horse skull discovered

On July 20, 1979, while checking roadcut exposures along Sapillo Creek north of Lake Roberts in southwestern New Mexico, Jon Sandor, research assistant, and John Hawley, environmental geologist, New Mexico Bureau of Mines and Mineral Resources, discovered bone fragments and teeth in Pleistocene steam-terrace deposits. The exposure was located in a position of active erosion along a major road in the Gila National Forest. Recovery of specimens was approved by the Mimbres District of the U.S. Forest Service.

On July 26, Sandor, Hawley, and New Mexico Bureau of Mines and Mineral Resources vertebrate paleontologist Donald Wolberg returned to the site and excavated the skull of a Pleistocene horse. The specimen (NMBM&MR VP 10001), the partial skull of a mature but relatively young horse, consists of a full palate with cheek teeth and partial braincase with right maxilla—lacrimal, frontal, and squamosal. The left side of the skull was severely eroded prior to recovery; only the left cheek tooth row and associated areas of the left maxilla remain. All upper per incisors were recovered in association with the skull, except for a single upper incisor that was found isolated, approximately 1 m from the skull. The premaxilla is represented by a mere fragment of bone associated with four of the incisors. The lower jaw and postcranial elements are absent.

This specimen represents a small horse, *Equus conversidens,* extant in the Yarmouthian to late Wisconsinan (Pleistocene) of Kansas, Oklahoma, Texas, New Mexico, Arizona, Florida, and the Valley of Mexico. Wisconsinan specimens are sometimes assigned to subspecies *E. conversidens littoralis* Hay. Preliminary analysis of VP 10001 indicates tooth morphology, measurements, and skull morphology well within the limits of *E. conversidens.* A detailed study of the material is in progress. ☐