Papers Presented to the

CONFERENCE ON
PLATEAU UPLIFT: MODE AND MECHANISM

Flagstaff, Arizona
14-16 August 1978

A LUNAR AND PLANETARY INSTITUTE TOPICAL CONFERENCE

Co-Sponsored by the
International Committee on Geodynamics,
Working Group 7

Hosted by the
U.S. Geological Survey, Geologic Division
Branch of Astrogeologic Studies

Universities Space Research Association
The Lunar and Planetary Institute
3303 NASA Road 1
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PREFACE

This volume contains papers which have been accepted for publication by the Program Committee of the Conference on Plateau Uplifts: Mode and Mechanism.

The Program Committee consists of K. Burke (*State University of New York*), G. Eaton (*U.S. Geological Survey*), E. A. Flinn (*NASA Headquarters*), P. P. Jones (*Lunar and Planetary Institute*), I. Lucchitta (*U.S. Geological Survey*), T. R. McGetchin, Chairman (*Lunar and Planetary Institute*), R. B. Merrill (*Lunar and Planetary Institute*), E. M. Shoemaker (*California Institute of Technology*), L. T. Silver (*California Institute of Technology*), G. A. Swann (*U. S. Geological Survey*), G. T. Thompson (*Stanford University*), and R. Young (*State University of New York*).

Logistic and administrative support for this Conference has been provided by P. P. Jones (*Administrative Assistant, Lunar and Planetary Institute*). This abstract volume has been prepared under the supervision of P. C. Robertson (*Technical Editor, Lunar and Planetary Institute*).

Papers are arranged alphabetically by the name of the first author.

A field guide is included at the back of this volume, followed by subject and author indices for the abstracts. A field map is attached to the inside back cover.

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RELATIVE UPLIFTS OF LARGE CONTINENTAL AREAS. Gerard C. Bond, Univ. of California, Davis, CA 95616.

Relative vertical movements of continental surfaces can be inferred by calculating percentages of flooding on continents at specific time intervals in the geologic past and then plotting the percentages on corresponding continental hypsometric curves. Regardless of whether sea level has changed during the geologic past, relative vertical movements between the continents is indicated if the points for a given time interval fall at different elevations; little or no relative vertical movement is indicated if the points fall at about the same elevation. The rationale for this interpretation is discussed in detail by Bond (1978a).

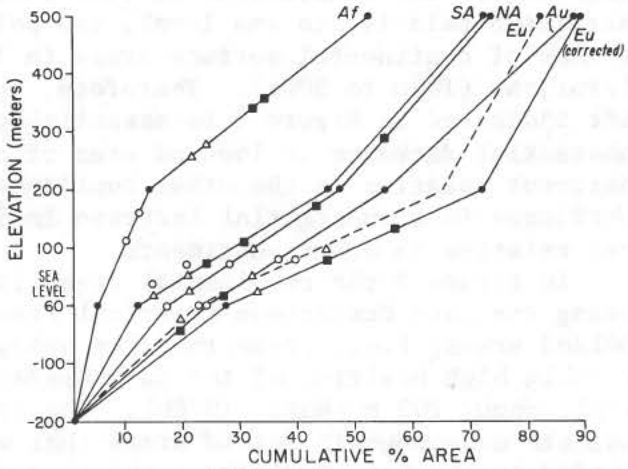

FIGURE 1

Percentages of flooding have been calculated for three time intervals and plotted on the appropriate hypsometric curves (Fig. 1). The dashed line for EU is the hypsometry for modern Europe; EU corrected is the hypsometry of Europe minus all areas south of the Alpine Zone as required if most of the Alpine areas were oceanic in the Late Cretaceous and Eocene (Dewey, et al., 1973). Solid dots are data points for the curves, solid squares are percentages of flooding for the Campanian-Maestrichtian, open triangles - Eocene, open circles - Miocene. The upper and lower points for each time interval on each curve are the percentages of flooding assuming that the shelves were 100% flooded and 50% flooded, respectively. Calculation of these two percentages for each time interval tends to compensate for unavoidable paleogeographic error in that the larger of the two percentages is a probable maximum and the smaller is a probable minimum estimate of the percentages of flooding.

The elevations to which the points correspond may be plotted against time for ease in interpretation (Fig. 2). The bars are error bars whose tops and bottoms correspond to the maximum and minimum percentage points, respectively, in Figure 1. The minimum bar (dashed) for North America in the Campanian-Maestrichtian inverval is an additional adjustment for error. This bar was calculated using the present erosional edges of the Late Cretaceous marine rocks, and it gives a significant underestimate of the flooded area. The elevation corresponding to the true area of flooding must lie between the solid and dashed bars.

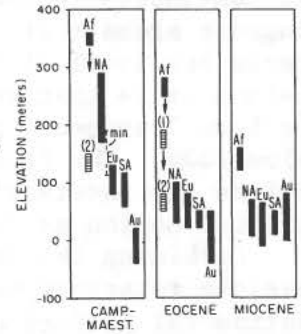

FIGURE 2

The position of Africa above other continents in the Miocene (Fig. 2) indicates post Miocene uplift in Africa. In the Eocene, correction for the post Miocene uplift of Africa (bar 1) does not restore Africa to the level of the other continents indicating post Eocene-pre Miocene uplift in Africa.

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Bond, G. C.

In the Campanian to Maestrichtian: (1) correction for post Eocene uplift (bar 2) restores Africa to the position of two other continents suggesting no recognizable post Maestrichtian uplift in Africa; (2) after correction for the Tertiary uplift of Africa, the high position of North America indicates post Maestrichtian - pre Eocene uplift in North America, and (3) the position of Australia below that of the other continents suggests that Australia was elevated in the Late Cretaceous and subsided substantially between the Late Cretaceous and the Eocene. These inferred movements do not necessarily involve all of the continental surface areas; moreover, because the data are calculated relative to sea level, the points only indicate net relative gain or loss of continental surface areas in lowland elevations (100m to 300m). Therefore, the uplift indicated in Figure 2 is essentially a substantial decrease in lowland area of a continent relative to the other continents; subsidence is a substantial increase in lowland area relative to other continents.

In Figure 3 the continental areas flooded during the Late Cretaceous (vertical lines) are lowland areas; i.e., areas that lay below the probable high position of the Late Cretaceous sea level, about 200 m (Bond, 1978b). The fine dots indicate non-orogenic upland areas that were not flooded in the Late Cretaceous and therefore lay above about 200 m. White areas are geologically unknown or orogenic regions. Note that the largest areas of flooding (western interior of North America, southern Europe, northern Africa) are adjacent to areas of convergence (arrows). Most uplands, however, are located where continents were rifting apart or were separated by narrow ocean basins (dashed lines) in the Late Cretaceous. Figure 4 shows the continents in their present positions. The horizontal lines are non-orogenic areas that, during the Late Cretaceous, were below the Late Cretaceous sea level of 200 m and are presently above 200 m; i.e., Late Cretaceous lowland areas that were uplifted and are now upland areas. Vertical lines are Late Cretaceous uplands that have subsided and are now lowland areas below 200m. The fine dots and solid patterns indicate areas in which vertical motions are indeterminante or areas that still have the same direction of vertical motion as during the Late Cretaceous.

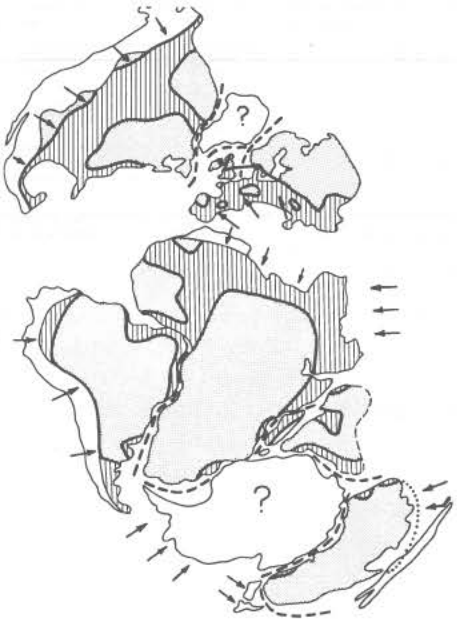

FIGURE 3

Combining the data and interpretations in Figure 1 - 4 suggests some possible relations between geodynamic processes and the uplift of large continental surface areas. The uplift of most of northern Africa shown in Figure 4 could be sufficient to produce the post Eocene uplift of Africa indicated in Figure 2. This uplifted area is the site of numerous Tertiary plateau, some with alkaline volcanic cover, and Tertiary to Recent rifts in incipient to early stages of evolution (Burke and Whiteman, 1973). Possibly, the African plateau are small areas with a large magnitude of uplift superimposed on a much broader area with a smaller magnitude of uplift. Similarly,

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BOND, G. C.

the area of post Cretaceous uplift in Central Europe (Fig. 4) is, in part, the site of numerous Tertiary rifts and alkaline volcanism, apparently related to collision in the Alpine Zone to the south (Dewey, 1977). The elevation of nearly all of Australia above the Late Cretaceous sea level of about 200m (Fig. 3) in contrast to large amount of lowland in Austraila now (Fig. 4) suggests the speculative possibility that nearly all of Australia was a plateau in the Late Cretaceous. This is not inconsistent with the fact that two thirds of Australia was surrounded by young ocean basins or active rifts (Fig. 3). The large uplifted area in the western interior of North America (Fig. 4) may account for the post Cretaceous - pre Eocene uplift relative to other continents indicated in Figure 2. In the western interior of the US parts of the uplifted area contain volcanics related to subducted slabs as well as plateau with alkaline volcanics and rifts and the uplift appears to have had a complex origin. There is no clear evidence relating the uplift in the western interior of Canada to similar complex processes.

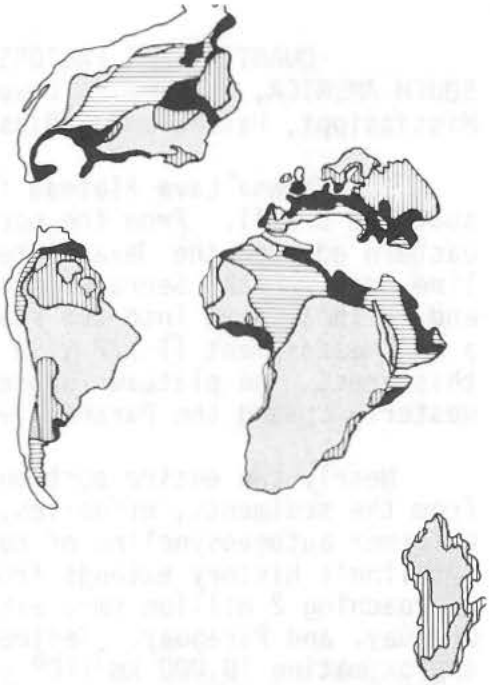

FIGURE 4

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QUANTITATIVE FACTORS IN THE FORMATION OF THE PARANÁ LAVA PLATEAU, SOUTH AMERICA, Richard L. Bowen, Dept. of Geol., Box 152, Univ. of Southern Mississippi, Hattiesburg, Mississippi 39401

The Paraná Lava Plateau forms a major portion of the Serra do Mar of southern Brasil. From the northern part of Rio Grande do Sul state, the eastern edge of the lava plateau and its continuation in the older crystalline rocks of the Serra do Mar of the Ponta Grossa Arch (state of Paraná) and northeastward into the states of São Paulo and Rio de Janeiro constitute a high escarpment (1 1/2 to 3 km above sea level) and drainage divide. From this crest, the plateau (whose surface area is $\sim$750,000 km^2) slopes 2-4 m/km westerly toward the Paraná River.

Nearly the entire portion of the present Paraná Plateau has developed from the sediments, effusives, and basement rocks involved in the history of a former autogeosyncline of considerably larger dimensions. The autogeosyncline's history extends from the Devonian to the Cretaceous and its area, approaching 2 million km^2, extends into the adjacent countries of Argentina, Uruguay, and Paraguay. Sediments collected in the autogeosyncline at rates approximating 10,000 km^3/10^6 yr in middle and upper Devonian time, 100,000 km^3/10^6 yr or more during a glacigene episode of latest(?) Carboniferous - earliest(?) Permian age, about 20,000 km^3/10^6 yr during the remainder of the Permian, and 5000 km^3/10^6 yr or less during the Triassic and Jurassic. The axis of the depocenter, where sediments to 3 1/2 km thickness accumulated, trends northwesterly, from the present coast of Paraná through the region of the Ponta Grossa Arch to the Paraná River. From this axis, the pre-lava sediments thin gradually southwestward and somewhat more rapidly northeastward.

The locale of greatest depositional accumulation clearly was a site of crustal weakness, for in late Jurassic to early Cretaceous time (120-130 million years ago), a large portion of the depocentral area was inverted into an ovoid of uplift whose major axis is alined with the maximum depocentral isopachs. The highest uplift of this structural inversion (the present Ponta Grossa Arch) is 7 1/2 km or more.

Although the autogeosyncline appears to have developed entirely on cratonic rocks, evidently the load of accumulated sediment (at least along the Ponta Grossa Sag, ancestral to the Ponta Grossa Arch) was sufficient, by late Jurassic times, to cause extensive magma formation in the simatic rocks of the deeper portions of the crust or uppermost mantle, for, accompanying the tensions of uplift, a great series of northwesterly trending fractures formed in the Ponta Grossa Arch region; from these, 1 million km^3 or more of basaltic lavas were extruded in association with the uplift. Individual lava sheets approach 200 m thickness and persist for more than 200 km; in fact, the lavas appear to have been so fluid that they spread up to 1000 km or more (into northern Argentina) on slopes which rarely exceeded 1°.

". . . PARANÁ LAVA PLATEAU . . ."

Bowen, R.L.

During the Cretaceous and Cenozoic, up to 9 km or more of erosion has exposed the basement rocks of the Ponta Grossa Arch. The form of the present Paraná Plateau is partly inherited from its earlier history, but it is also due in part to the formation of Cenozoic coastal half-grabens and in part to NNE'ly trending fracture systems (approximately paralleling the present coast) which date back at least to the early Paleozoic but along which recurrent movements have taken place even into Neogene times.

INTRA-PLATE DYNAMIC PROBLEMS WITH REGARD TO CRUSTAL STRUCTURE P.J. Burek, Research School of Earth Sciences, The Australian National University, Canberra ACT 2600, Australia.

The basic result of fault-plane solutions and that of in situ-stress measurements is of great importance: they show - wherever data is analysed - that globally consistent tectonic plates are not under tensile stress environments, but are exposed to horizontal compression. Especially, epeirogenic structural features of Caeno- to Mesozoic age in Arabia (shield warping), Central Europe (shearing, continental rupture), Central Australia (block tilting) imply that these horizontal compressional stress patterns vary with respect to time in intensity as well as direction. Pronounced directional symmetrics between these epeirogenic features and neighbouring oceanic ridges imply that the source for the horizontal compression of the crust originates in and is associated with mid-oceanic ridges and their spreading activities. The latter observation and the compressional nature of the continental epeirogenic structures lead to the conclusion that tectonic plates are pushed away from the oceanic ridges, thus relating epeirogeny to a predominantly thermal driving mechanism involving the overturn or convection of oceanic crust.

There are four major epeirogenic reactions of continental crust associated with the above outlined horizontal compression: 1. crustal warping (well developed on and around the Arabian Shield); 2. shearing along diagonally arranged fault-zones (predominant in the Central European block-mosaic); 3. block tilting associated with a slight up-thrust component in areas where suitable faults pre-exist (creating a basin and range-type morphology in Central Australia); and 4. continental rupture in areas of anomalous stress transfer on a craton (i.e. Rhine Graben, Germany, Benue Trough, Nigeria, and possibly Spencer Gulf, South Australia).

Even though it appears that a geodynamic model consistent with epeirogenic movements can be found, it raises several fundamental questions with regard to crustal properties: Do the tectonic responses of shield areas to lateral compression require almost immediate isostatic adjustment? What crustal mechanisms would facilitate the postulated relationship between epeirogenic movements (in shield areas) and the sources (oceanic ridges) often several thousand kilometers away?

Long distant crustal seismic profiling in Siberia and Scandinavia generally shows that the Moho-morphology reverses the surface morphology and/or geological uplift and basin structures. This implies that in the shield areas observed tectonic surface movements are isostatically balanced by Moho-migrations.

In Europe, Asia, N.America, S.Africa and Australia there are regionally seismic and/or magneto-telluric indications (reduced velocities, increased conductivity) for a layered sialic crust:

INTRA-PLATE DYNAMIC PROBLEMS WITH REGARD TO CRUSTAL STRUCTURE

P.J. Burek

two sialic inversion channels in depths of ± 20-25km and 8-15 km, usually in areas of tectonic activity are inferred. One possible explanation is that these layers are caused by zonal release of interstitial OH^- and enrichment of connate H_2O under tectonic activation; this would relate the layers to metamorphic processes. H_2O(-vapour) presence and pressure in smallest amounts would reduce rock-strength and facilitate translational gliding and thus allow tectonic adjustment. Considering a layered crustal model and the possibilities of the presence of H_2O it is tempting to see analogies between epeirogenic reactions in shield areas and those of sediments to lateral compression: The tectonic inventory is identical, the scaling is vastly different.

Another consequence of crustal H_2O-release under tectonic activation is the lowering of melting points, which is of relevance with respect to crustal (sialic) derived volcanism. In early rifting, i.e. pre-spreading stages porphyric, rhyolitic volcanism, including ring dykes, granitic intrusions and hydrothermal activity are often associated with crustal warping, fracturing and shearing (Oslo-Area, Jos-Plateau, Trap- and Aden Volcanics of Ethiopia and Jemen, etc.).

Metamorphic H_2O-release in the earth's crust is certainly relevant to intra-plate dynamic processes. An explanation for the apparently zonal H_2O-enrichment is required. Was the crustal H_2O-content constant versus time? If higher in the past what are the consequences with respect to crustal mobility, heat conductivity, geodynamic processes etc.? Clearly, better understanding of the relationships between tectonic, magmatic, metamorphic, rock-mechanical, geophysical and geochemical P-T reactions, especially within the sialic part of the earth crust, is needed.

For references, further details and illustrations see:

P.J. Burek: Plattentektonische Probleme in der weiteren Umgebung Arabiens sowie der Danakil-Afar-Senke, Geotekt.Forsch. 47, 1-93, 1974.

P.J. Burek: Structural Deduction of the Initial Age of the Atlantic Rift System, in: Implications of Continental Drift to the Earth Sciences, D.H. Tarling and S.K. Runcorn, eds., Vol.2, 815-830, Academic Press, 1973.

CATEGORIES OF PLATEAUS ON EARTH, Kevin Burke, Dept. of Geological Sciences, S.U.N.Y. at Albany, 1400 Washington Ave., Albany, NY 12222

Arthur Holmes defined plateaus as broad uplands of considerable elevation. An initial distinction among terrestrial plateaus can be drawn between those on oceanic and continental lithosphere.

Plateaus on the ocean floor which is the youngest part of the lithosphere are, paradoxically, the oldest plateaus on earth because they escape the rapid subaerial erosion to which continental plateaus are subject. Oceanic plateaus range in extent from very large seamounts to areas approaching continental dimensions (> 10^6 sq. km). The elevation of oceanic plateaus over surrounding ocean floor can usefully be analyzed in terms of the age/depth curve and related estimates of crustal thickness are closely similar to those obtained by seismic refraction. Winterer has shown that some Pacific plateaus (notably the Manihiki and Ontong Java plateaus) may have been made at oceanic ridges and has suggested that they resemble Iceland in being the result of very large amounts of vulcanism at a nodal area along an oceanic ridge. An alternative view (as for Iceland) is that at least some Pacific plateaus are continental and possibly fragments of a large continent.

Where Pacific plateaus have reached subduction zones their buoyancy has been associated with modifications in tectonic processes. The most extreme instance of this association is seen in the Caribbean where all normal ocean floor appears to have been subducted leaving the floor of the Caribbean Sea occupied by a buoyant residuum of ocean floor plateau type.

A challenging and relatively little studied group of plateaus are those lying slightly below sea level and at or close to the edge of a continent. Some are associated with rifted margins (e.g. the Rockall and Exmouth plateaus) and others with convergent margins (e.g. the Campbell Plateau and Chatham Rise).

Using Holmes' definition continents could be considered as plateaus, relative to the ocean floor, the elevation difference being a product of buoyancy. Within the continents themselves an important generalization is that plateau elevation must be a relatively recent phenomenon (not more than 30 to 40 m.y. old at most) because subaerial erosion would have removed older elevations from earth's surface. Older plateaus could, however, be maintained by continuous elevation or revived by repeated or episodic uplift.

A distinction between continental plateaus associated with plate-margins, either divergent (e.g. the Ethiopian Plateau) or convergent (e.g. Tibet, Iran, Shillong, the Altiplano) and those away from plate-boundaries is obviously important but hard to apply in areas such as Western U.S.A. and Central Asia where plate-boundaries are diffuse.

The central theme of our conference can be interpreted as the study of the last class of plateaus: those lying within continents and remote from plate-boundaries. These are beginning to respond to an integrated approach to their study. Gravity and seismic refraction are characterizing the objects to depths of tens of kilometers and geomorphologic and stratigraphic studies (especially in bordering areas) are defining rates, styles and durations of uplift. Where igneous rocks associated with plateau formation occur they and the xenoliths they contain permit structural inferences

CATEGORIES OF PLATEAUS ON EARTH

Burke, K.

extending to depths as great as 100 km. Igneous rocks, their structural features and distribution may also illuminate the timing and mechanism of uplift.

We can learn much about plateau origin by concentrating on the timing of plateau formation in relation to other tectonic events within the global framework. For example, the great plateaus of the African plate, where dateable, appear to have begun to form about the beginning of the Neogene. Evidence from the ocean floor and paleomagnetism suggests that this is the time when the African plate came to rest with respect to the underlying convective circulation pattern. Recognition of this coincidence in timing leads to the inference that the plateaus and swells of Africa may be the relatively simple expression of a thermal pattern imposed by convection on the bottom of the lithosphere. This idea finds some support in regularities discernable in the horizontal distribution of African plateaus.

GEOPHYSICAL CHARACTERISTICS OF THE COLORADO PLATEAU AND ITS TRANSITION TO THE BASIN AND RANGE PROVINCE IN UTAH.

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Department of Geology and Geophysics, University of Utah
Salt Lake City, Utah 84112

Geodynamic models used to explain the mode and mechanism of plateau uplift must satisfy certain geological, geochemical and geophysical constraints. These constraints will apply to the interior of the uplifted region itself but may be most revealing at province boundaries where the width of transition zone may help to discriminate between crustal, lithospheric or sub-lithospheric mechanisms. Accordingly we have made a compilation of some geophysical parameters for the Colorado Plateau uplift in southwest Utah paying particular attention to the change in those parameters across the Colorado Plateau - Basin and Range transition.

The region from which we have drawn our data is central and southern Utah between latitudes 40°N and 37°N (Fig. 1). Within this region the north-south Wasatch Line divides the Colorado Plateau from the Basin and Range physiographic province. Composite east west profiles of crustal structure, heat flow, seismic energy release, gravity and elevation are shown in Fig. 2. Distances are measured east west from the Wasatch line.

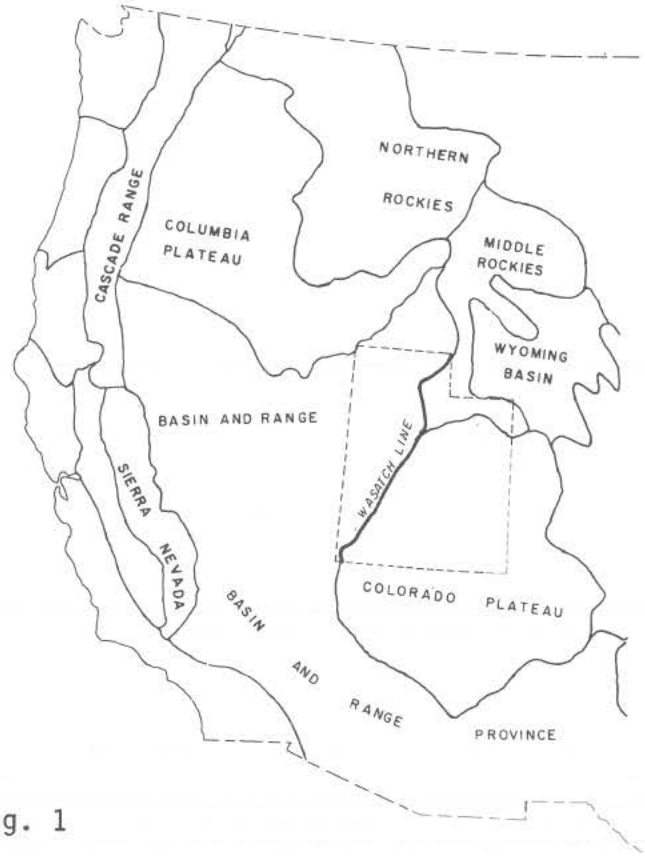

Fig. 1

Figure 2(a) shows crustal structure based on three seismic refraction profiles: (A) Delta, Utah; (B) Wasatch front, Utah, and (C) Hanksville, Utah. The Colorado plateau has a thick crust (43 km) and high Pn velocity (7.8-8.0 km/sec) compared to the northern Basin and Range which has relatively thin crust (28 km) and low Pn velocity (7.5 km/sec). The transition Wasatch Front zone has even thinner crust (25 km) and lower P velocity of 7.4 km/s.

Twenty five heat flow results from Utah have been combined with twelve published values to construct the east west heat flow profile shown in Fig. 2(b). Characteristic heat flow brackets for the Colorado Plateau and Basin and Range can be taken as 40-60 mW m^{-2} (1.0-1.5 HFU) and 75-100 mW m^{-2} (1.8-2.4 HFU) respectively (shaded regions on figure). The width of the heat

GEOPHYSICS COLORADO PLATEAU - BASIN RANGE

Chapman, D. S., et al.

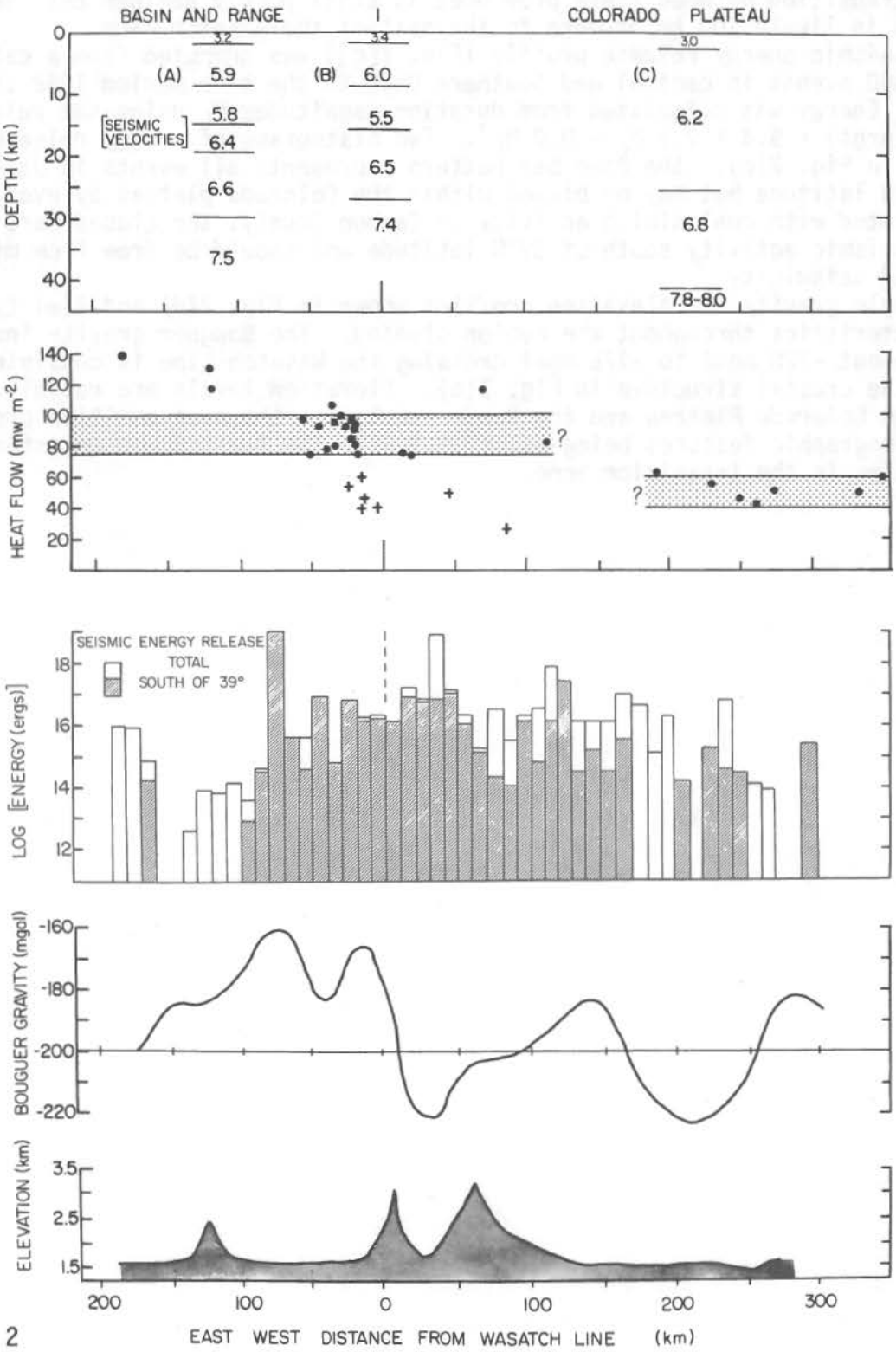

Fig. 2

flow transition between these provinces is still poorly defined but the transition is likely 100 km or more to the east of the Wasatch line.

A seismic energy release profile (Fig. 2[c]) was computed from a catalog of >1500 events in central and southern Utah in the time period 1962 through 1977. Energy was calculated from duration magnitudes M_L using the relation $\log E(\text{ergs}) = 9.4 + 2.1\, M_L - 0.0\, M_L^2$. Two histograms of energy release are shown in Fig. 2(c): the open bar pattern represents all events in Utah south of 40°N latitude but may be biased within the Colorado plateau by events associated with coal mining activity in Carbon County; the closed bars represent seismic activity south of 39°N latitude and should be free from mining related seismicity.

Single gravity and elevation profiles shown in Fig. 2(d) and 2(e) typify characteristics throughout the region studied. The Bouguer gravity increase from about -220 mgal to -175 mgal crossing the Wasatch Line is consistent with the crustal structure in Fig. 1(a). Elevation levels are roughly equal for the Colorado Plateau and the Basin and Range, the most positive pronounced topographic features being associated with the faulted and thrusted mountains in the transition zone.

THERMAL ORIGIN OF THE PLATEAUS SURROUNDING MID-PLATE, HOT-SPOT VOLCANOES, S. Thomas Crough, Geophysical Fluid Dynamics Laboratory, P.O. Box 308, Princeton University, Princeton, New Jersey 08540

Most of the volcanic centers identified as fixed hot-spots cap plateaus about 1000 km wide and 1 km higher than their surroundings. Gravity and subsidence data suggest that this type of plateau or swell is caused by a broad-scale reheating of the lithosphere. Inversion of the measured free-air gravity over the swells beneath the Hawaiian, Cook-Austral, Bermuda, and Cape Verde Islands indicates that if the swells are compensated by a mass deficiency at a single depth, then that depth is about 70 km. Recent satellite altimetry profiles of the geoid over these swells gives the same depth results when inverted. That is, the bulk of the compensation is probably within the lower part of the lithosphere.

The height of the Hawaiian Swell above its surroundings gradually decreases along the strike of the Hawaiian Islands as the islands and guyots get older. Beneath the Emperor Guyots the swell is no longer apparent but the great depths of the tops of these guyots indicate that they once were on a plateau similar in height to the swell at Oahu. The observed decrease in elevation of the Hawaiian Swell is quantitatively consistent with vertical cooling of the lithosphere after an episode of reheating over an active hotspot. The same hot-spot thermal model explains the deep guyots of the western Pacific and appears to be the source of the previously infered Darwin Rise. The concept may also be applicable to some continental plateaus such as the Ahaggar and Ethiopian Swells of Africa.

LITHOSPHERIC AND CRUSTAL EVOLUTION OF CENTRAL MEXICO

J. Urrutia Fucugauchi, School of Physics, University of New Newcastle upon Tyne, NE1 7RU, England. and Instituto de Geofisica, U.N.A.M., Mexico 20 D.F. Mexico

A simple model of volcanic-capped plateau uplifts in terms of plate subduction and lithospheric and crustal evolution is proposed, and a detailed test for the Central Mexico plateau is presented.

The Mexican volcanic belt (MVB) of central Mexico is a linear plateau, about 1000 km long and variable wide up to 200 km, with a maximum elevation of about 5675 m asl. It extends westward from the Gulf of Mexico to the Pacific Ocean, where it intersects the Sierra Madre Occidental of northwestern Mexico. The plateau consists of a number of inactive and active volcanoes, which have been built up by dominantly andesite and dacite eruptions. The age of this volcanic activity ranges from Oligocene to Present, with three main periods of widespread activity, viz. Oligocene-Miocene, Late Miocene-Pliocene and Quaternary. In addition, there are several monogenetic scoria cones, generally younger ages, of more basic composition. The plateau is capped by almost continuous exposures of volcanic rocks and underlain by Cretacic folded and eroded marine sediments. The MVB is related to subduction of the Cocos plate at the Middle America trench (MAT). To the west the plateau lies close to the junction between the MAT and the East Pacific rise (EPR). By extrapolating in time, subduction of the EPR at the MAT may occur in the near future. $^{87}Sr/^{86}Sr$ ratios lay in the range 0.7032-0.7045 supporting an origin associated with plate subduction.

Gravimetric results indicate that a progressive increase in elevation of the Valley of Mexico near the central portion of the MVB relative to Acapulco in the Pacific coast has been occuring during at least the last two decades. Calculations using a finite-element model show that this change is not fully explained by the pre-seismic stress-strain field due to the subduction process. On the other hand, the Bouger gravity anomaly in the MVB suggests the presence of a regional vertical force acting beneath it. The gravity anomaly is similar to that found in the Colorado plateau.

Geochemical results indicate that a progressive crustal and lithospheric thinning has occurred since the Oligocene in the MVB . The crustal thickness has changed from more than 40 km to less than 30 km. The depth to the Benioff zone has decreased from about 200 km to about 150 km which correlates with a decrease of Benioff zone dip angle. The regional pattern indicates a flattening of Benioff zone dipand increasing of subduction rate from the Pacific to the Gulf of Mexico. This, combined with the proximity of the EPR to the MAT, results in increasing thermal effects which cause a lithospheric and subcrustal erosion. The increase of temperature versus depth beneath the MVB is higher than that of the Basin and Range province. The goetherm model implies a partial melting at the base of the crust. The heating of the crust results in its thinning and causes a tensional tectonism by the upward and

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lateral flow of decreasing density and viscosity molten material. The upward flow is responsible for the plateau uplift. If the process continues and the EPR is underthrusted beneath Mexico, the thermal effects will further increase resulting in a higher subcrustal erosion rate and extensive tensional tectonism. The future configuration may be similar to that in the southwestern United States, and eventually a continental breakup and subsequent drifting may occur in the MVB region.

In addition, it is suggested that a continent/continent colision occurred in central Mexico during latest Late Cretaceous so that this zone may eventually experience a complete Wilson cycle of collision and rifting with the associated effects for lithosphere and crust evolution of consolidation, thickening, depletion and thinning. The cycle is mainly controled by the plate subduction evolution which depends on the Benioff zone dip changes and the trench-rise distance (oceanic plate age).

PETROLOGIC CONSTRAINTS FOR UPPER MANTLE MODELS OF THE COLORADO PLATEAU. H. Helmstaedt and D.J. Schulze, Department of Geological Sciences, Queen's University, Kingston, Ontario, Canada, K7L 3N6.

Ultramafic xenolith suites from kimberlites, minettes, basalts, and latites have provided numerous samples of the upper mantle under the Colorado plateau. These have been studied extensively not only to gain information about the petrologic composition of the upper mantle, but also to yield clues as to the geodynamic processes which may have been responsible for the existence of the plateau.

As present interpretations differ widely, even when based on similar xenolith suites (1, 2, 2, 4, 5, 6, 7, 8), the nature of constraints that xenoliths can provide for models of upper mantle composition and processes must be carefully evaluated. Considering the erratic nature of the sampling process, it is not surprising that true constraints are relatively few. The host rocks of the xenoliths range in age from Oligocene to recent and have sampled the mantle at different depths in widely spaced localities. Differences in rock type of the transport medium control the extent of xenolith-host rock reaction and speed of transport to the surface, thus causing the most severe sampling bias.

The kimberlite of the Navajo field were emplaced fast and at relatively low temperatures (1, 2). They contain the broadest spectrum of possible mantle rocks including metamorphic eclogites and spinel- and garnet-bearing peridotites many of which have hydrous alteration assemblages (6, 7, 8, 9, 10,). Minette diatremes, though closely related to kimberlites in space and time, have a much more restricted inclusion suite (11, 12). The ultrabasic xenoliths lack low-temperature hydrous alteration assemblages, and eclogites are absent with the exception of an altered specimen in the felsic minette of Buell park (11). Latites in Chino Valley, of similar age as kimberlites and minettes, contain eclogites which have been altered and partially melted to such a degree that their nature prior to inclusion is unclear (13, 14). Inclusion suites in basalts, whether Tertiary (11), or more recent (15), contain no eclogites but consist mainly of spinel-bearing lherzolites and pyroxenites. Metamorphic eclogites, therefore, do not survive in high-temperature transport media. Their abundance and distribution under the Colorado plateau can be evaluated only if xenolith suites of more or less coeval, relatively low-temperature host rocks are compared. Thus between 30 and 25 m.y. ago eclogites were common under the Four Corners and Chino Valley, but relatively rare under the Zilditloi field. Xenolith suites from younger volcanic rocks provide no evidence as to whether similar eclogites are absent or still existent under the present plateau. The relative proportion of eclogite to ultrabasic rocks under the Four Corners is difficult to estimate, as the hydrated ultrabasic rocks disintegrate much more easily than the tough eclogites.

Although the kimberlites appear to provide the least sample bias of any of the transport media, there is little agreement about the depth of upper mantle column sampled and the origin and tectonic significance of the xenoliths. Geothermometry and geobarometry on minerals from xenoliths and xenocrysts have been used by McGetchin and Silver (1, 2) to infer the P-T conditions at which the assemblages equilibrated. This model (1, 2) assumes that individual rock

types were incorporated into the kimberlite at a depth indicated by the equilibrium pressure of the anhydrous mineral assemblages. The depth of origin of the kimberlite, thought to correspond to the P-T conditions of the anhydrous garnet lherzolite assemblage, is inferred to be between 150 and 200 km.

A model by Smith and Levy (7, 8) based mainly on the inclusion suite from Green Knobs, considers the hydrated state of many of the ultrabasic xenoliths and explains it by mantle diapirism prior to incorporation by the kimberlite. The low-temperature eclogites from the Four Corners pipes are thought to have originated by slow cooling of rocks intruded into the lower crust or upper mantle in areas of a low geothermal gradient (16).

Another model, based on the similarity of the xenolith suite to rocks from metaophiolite complexes in orogenic belts, interpretes the low-temperature eclogites as fragments of subducted oceanic lithosphere (3, 4, 5). This model was supported by Mercier (6) on the basis of pyroxene geobarometry. Mercier emphasized that the samples have undergone a hydrous alteration history at depths much shallower than indicated by goebarometry on the anhydrous assemblages. As shown by Helmstaedt and Schulze (9, 10), all mineral assemblages and metamorphic reactions in ultrabasic rock types are known in high-pressure metaophiolites on the earth's surface and are compatible with the interpretation of the eclogites. Recently collected xenoliths provide further evidence for the metaophiolite model. Lawsonite rocks (eclogites with >50% lawsonite) from Moses Rock have the chemical composition and mineral assemblage of metamorphosed rodingites demonstrating that prior to metamorphism basic igneous rocks were metasomatized while in contact with serpentinites (17). A xenolith from Mule Ear consists of albite, clinopyroxene (diopside core, sodic rim), garnet and rutile. This rock represents an intermediate state in the garnet-eclogite transition and confirms the progressive metamorphic nature of the low-T eclogites. The same rock contains late sodic amphibole and sphene rims around rutile similar as in Franciscan eclogites.

There can be little doubt that the ultramafic xenolith assemblage from the kimberlites corresponds to the lithologic assemblage 'metaophiolite' recognized in orogenic belts on the earth's surface. As such suites are not known in other geologic settings, constraints for upper mantle models are severe. All models must account for the existence of metaophiolites under the plateau between 30 and 25 m.y. ago. As field relationships in exposed metaophiolites are extremely complex, all models must accept that contact relationships between basic and ultrabasic rocks may be equally complex at depth. Upper mantle stratigraphy based on geobarometry is unrealistic, because unaltered rocks recording one set of P-T conditions may be in close contact with highly altered rocks recording another set. The depth of the upper mantle column sampled by the kimberlite is not known. No sample need have come from a depth greater than compatible with the hydrous alteration assemblages.

The petrogenetic history of the xenoliths and their geodynamic significance is as problematic as in exposed metaophiolites. Many such complexes have been accepted as fragments of former oceanic lithosphere, but in many others deformation and metamorphism are too extreme to recognize original rock types and contact relationships, and the origin remains disputed. Whether the model that some of the xenoliths are derived from a shallow subduction zone is

realistic, remains to be tested. Its compatibility with recent geotectonic models of the south western United States (18, 19) suggests that shallow subduction should be considered in solving the puzzle of the tectonic evolution of the Colorado Plateau.

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QUATERNARY UPLIFT OF THE RHENISH SHIELD IN CENTRAL EUROPE: DATA AND INTERPRETATION

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The high plateau between Mainz and Bonn, Kassel and Luxemburg is termed the Rhenish shield. This about 100 x 200 km wide block is composed of shists and slates of prevalently Devonian age that were strongly folded by the Hercynian orogeny. During the Mesozoic the area was more or less mainland. In Tertiary time it was a flat platform, marginally flooded by Oligo-Miocene marine transgressions, whereas the central part was an area of fluvial gravel accumulation. Wide-spread volcanic eruptions of mainly basaltic composition pierced the crust in different episodes during Eocene, Oligocene, and Miocene (Cantarel & Lippolt 1977). During the Pliocene, forerunners of the present rivers Rhine and Mosel traversed the platform and related fluvial terrasses are found about 230-280 m above the present river level (Quitzow 1974). A sequence of Lower Pleistocene terrasses ranges between 130 and 220 m above the actual river plains. The 150 m terrasse corresponds to the about 600 000 years old fossiliferous sands of Mosbach (Bibus & Semmel 1977). The antecedent river valleys of the Rhine and Mosel rivers and their tributaries indicate an Upper Pliocene uplift of the shield of about 50 m. In Lower Pleistocene time, the amount of uplift was about 80 m, and after the deposition of the about 600 000 years old level of the main terrasse a further 150 m uplift is indicated. Widespread volcanic action accompanied the beginning of rapid Quaternary shield uplift about 500 000 years B.P. (Windheuser 1977). The youngest volcanic eruptions are that of the maar craters in the Eifel area, which culminated about 11 000 years B.P. (Erlenkeuser et al. 1972), and became extinct about 8000 years B.P.

The shield area is framed by active rift valleys, the Rhinegraben in the South and the Lower Rhine embayment in the North (Illies 1977). In these rift valleys Pliocene to Recent subsidence evolved contemporaneously with the shield uplift. The fault breccia separating the Rhinegraben and the Rhenish shield was described first by Goethe in 1817. Both rift segments are seismically active and a belt of earthquake epicenters connects the two grabens, traversing the Rhenish shield (Ahorner 1975). In some areas of the shield the seismic activity may be related to normal faulting of Holocene age (Stengel-Rutkowski 1976).

To describe the uplift phenomenon in detail, to interprete the data, and to model the causes of shield uplift, a 5 years program was founded by the Deutsche Forschungsgemeinschaft (German Research Society) 2 years ago. The work is supported by an annual amount of about 0,6 to 1,0 million dollars. It comprises geodetic studies to investigate the active rates of vertical movements (Mälzer & others), geomorphologic studies to reveal the deformation and ages of river terrasses (Semmel & others), and neotectonic observations in areas of active faulting (Meyer, Müller, Negendank & others). To study the regional stress conditions and the strain release a program of in situ stress determinations (Greiner) as well as a microseismic array (Ahorner, Bonjer & others) was incorporated. The project comprises petrological investigations of the Tertiary volcanics (v. Gehlen, Huckenholz, Wedepohl) and especially of the Quaternary eruptions (Brunnacker, Jasmund, Schmincke). Radiometric dating of the volcanics will be done by Lippolt & others. Heat flow measurements are carried out by Haenel. To study the structure of the crust and upper mantle a magnetotelluric survey is under way (Untiedt). The most expensive project is a long-ranged refraction seismic profile from France and Belgium-Luxemburg crossing ENE-ward the whole Rhenish shield up to about the Harz mountains (Fuchs, Prodehl). Special explosion seismic experiments are investigated across the Hunsrück fault zone in the South and near Aachen in the North (Meissner, Murawski). Modelling by using all the data available is being undertaken by Jacoby, Neugebauer & others.

The results of this multidisciplinary work, coordinated by the author, will be available for publication not earlier than 3 years from now. As a preliminary working hypothesis the following model is under discussion. Since end-Miocene time, the block mosaic of the Alpine foreland was pushed forward in northwestward direction about 10 km (Illies 1978). The magnitude of block motion decreased towards the North, having been gradually diminished by sinistral shear along the Rhinegraben, by fault and joint displacements, and by local folding. A residual amount of horizontal displacement of only a few km reached the southern edge of the Rhenish shield in the Frankfurt area during the Pliocene. By this, the Rhenish shield has been shifted northwestward and rotated anticlockwise. Consequent shear heating on the base of the lithosphere (or crust) caused widespread volcanic action, generated from the magmatic level of shear heating. Shear heating additionally caused phase transformations and consequent processes of isostatic rebound and uplift. To investigate this, current work is especially focussed upon the stress/strain transmission along the southern edge of the unit in the Frankfurt

area. Furthermore, detailed geochemical studies try to reveal the depth, ages, and distribution of the magma source of the Quaternary volcanic eruptions. And from the magnetotelluric survey and the refraction seismic experiment it is hoped to learn more about the depths of possible layers of low-resistivity or inversion respectively. Moreover, it is under study if there are some chronological differences of the beginning, rates and actual amounts of shield uplift as related to the possible location of active horizontal strain transmission to the concerned block unit.

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PLATEAU UPLIFT IN PENINSULAR INDIA

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The Indian subcontinent is flanked in the north by the great Tibetan Plateau, the largest in the world, rising to an elevation of 5 km to the north of the Himalayan mountain range denoting the Plate boundary between the Indian and Eurasian Plates, and the Shan Plateau on its eastern side with a smaller elevation of 2.5 km. The peninsular shield of India within the Indian Plate has also witnessed plateau uplift over an extensive region away from the subduction zone. The major plateau regions in peninsular India comprise the Deccan plateau and Karnataka plateau in south India and the Chotanagpur plateau and Shillong plateau in eastern and north-eastern India respectively. These have been associated with prominent vertical movements of the epeirogenic type, especially during the Cenozoic period, which have continued through the Quaternary and Recent to the present time as evidenced by geomorphic features and seismicity.

The Deccan plateau which has an average elevation of 600-1000 m above mean sea level is mostly covered by plateau basalts of the Deccan Trap which also extend into the Kathiawar peninsula of western Gujarat. The vents and fissures through which the laves were extruded are presumed to be located in the western parts of the Narmada valley and the adjacent parts of the Bombay coast. The rock varies from basalt to dolerite extruded from a predominently tholeitic magma and the flows vary in thickness from 2 to 100 m. A conspicuous domal feature occurs in the Ambadongar area of Gujarat in the western extremity of the Narmada valley, rising to an elevation of 600 m above mean sea level with Cretaceous sediments showing quaquaversal dips of 60° intruded by trappean dykes and sills which in turn are overlain by basalts. Post-trappean intrusives of basic alkaline rocks with soda rich pyroxines, nepheline and sodalite are exposed along the periphery of the dome which is also characterised by fluorite and carbonatite occurrences. The Girnar hill of Junagadh in Kathiawar further to the west, comprising basalts, andesites and acid lavas has a circular outline covering an area of roughly 200 sq km, rising to an elevation of 1000 m. The basalts over this hill again show quaquaversal dips with intrusives of plutonic rocks including syenite, nepheline syenite, olivine gabbro and lamprophyres. This feature in the Deccan trap region is believed to represent a central type of non-explosive volcanic activity towards the close of the Deccan trap episode.

The Deccan trap region and the Narmada-Son valleys have been covered by systematic gravity surveys and the trap thickness in the Deccan

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plateau has been determined at a number of points by refraction seismic soundings. The Bouguer gravity map of the Deccan plateau presents a number of prominent gravity 'highs' and 'lows' suggestive of marked zones of uplift and subsidence and the seismic soundings indicate trap thickness varying from about 100 m in the marginal portions within the trap boundaries in the south and the east to more than 1000 m in the western parts of Maharashtra. A major deep, buried north-south fault has been indicated along the Bombay coast, its southern portion passing through the western proximity of the Koyna earth-quake zone. Marginal north-south as well as east-west faults have also been delineated by gravity and seismic surveys in the off-shore areas to the west of the Bombay coast south of the Cambay graben and to the south of the Kathiawar peninsula.

The gravity data over the Narmada-Son valleys which constitute a major WSW-ENE lineament over the northern borders of the Deccan plateau extending over a distance of roughly 2000 km have clearly brought out the fault systems of this rift which are broken in parts. The rift appears to shallow up towards the western extremity of the Narmada valley near the Arabian Sea cost. This rift zone is generally associated with mild seismicity but for the shallow earthquake of magnitude 5.4 which occurred near Broach in 1970. The occurrence of fluorite and carbonatite in the western extremity and diamond bearing kimberlite pipes in the eastern extremity of this rift zone is of great significance.

The Karnataka plateau contiguous to the Deccan plateau to its south has also an average elevation of 600-1000 m and occupies the major part of the Precambrian gneisses, granties and charnockites. It is characterised by some major plutonic masses apparently connected to deep-seated batholiths, which are reflected in the Bouguer gravity map as strong negative anomaly zones. This plateau region is also characterised by prominent geomorphic features and mild seismicity.

The Chotanagpur plateau in eastern India rises to an elevation of 1000 m with four characteristic interplanar slopes with elevations of 940-1000, 600-700, 230-300 and 130-160 m above mean sea level the successive planar faces being separated by steep gradients and several water falls. Vertical movement of the order of 1 cm per 100 years appear to be taking place in this plateau region which is also associated with mild seismicity.

The Shillong plateau in the north-eastern part of the peninsula is an epeirogenically uplifted horst block which has witnessed plateau basalt volcanism over its southern margin, giving rise to the Sylhet traps. This plateau rises to a maximum elevation of nearly 2000 m and is located in a zone of intense seismicity. Repeated geodetic levelling conducted during

the past 70 years across this plateau has indicated a rise of 2.5 cm over this period.

The whole of south peninsular India including the Deccan and Karnataka plateau is a region of particularly pronounced negative gravity anomalies which extend southward into the Indian Ocean. The cause of this anomaly clearly appears to be within the mantle, the processes being probably associated with hot spots and mantle plumes which appear to characterise the uplift of the Shillong plateau also. The particularly marked negative gravity anomalies over the Narmada-Son rift zone and the peninsular plateau region may also probably be indicative of a thinner lithosphere.

REGIONAL VARIATIONS OF THE LOWER CONTINENTAL CRUST: INFERENCES FROM MAGMAS AND XENOLITHS

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Lower crustal rocks occur as xenoliths in volcanic rocks and kimberlites, and provide direct evidence of rock types and processes that occur in this otherwise inaccessible region. Crustal-derived melts provide a second line of evidence. Xenoliths and crustal magmas indicate that the lower crust is complex, as expected. By regionalizing our approach, more homogeneous lower crustal volumes can be characterized. The regions chosen are: converging plate margins, rift valley environments, and intraplate areas underlain by polymetamorphosed lower crust. Within each region, it seems well within our reach to characterize the "protoliths" of deep crustal xenoliths as to their origin: sedimentary and igneous. Often, igneous rocks are predominant. The frequent appearance of residual crust (sedimentary or igneous rock with melt removed) and frozen basic rocks among deep crustal xenoliths is expected according to many crustal models.

Investigations into the origins of lower crustal rock suites, the age relationships between crustal units, and the temperature strain history of the crust are promising research topics for the next decade.

REGIONAL CRUSTAL STRUCTURE OF THE COLORADO PLATEAU, G.R. Keller, Dept. of Geological Sciences, Univ. of Texas at El Paso, TX 79968; L.W. Braile, Dept. of Geosciences, Purdue Univ., West Lafayette, IN 47907; P. Morgan, Depts. of Earth Sciences and Physics, New Mexico State Univ., Las Cruces, NM 88003

Surface wave dispersion and seismic refraction data show that the crust of the Colorado Plateau is approximately 40km thick. This thickness is clearly greater than that found in the Basin and Range Province(30km) which bounds the plateau on the west and south. Results from recent seismic studies indicate that the Rio Grande Rift, which bounds the plateau on the east, also has a thinner crust (30-35km) than the plateau. The northern boundary of the plateau is not associated with a major change in crustal thickness. However, a change in crustal composition occurs beneath the Uinta Basin.

In general, belts of active seismicity and Cenozoic faulting are associated with those boundaries of the Colorado Plateau which involve subtantial crustal thinning. At both the northwestern and southwestern boundaries of the plateau, seismic data indicate that mantle upwarps associated with thinner Basin and Range crust extend as much as 100km into the plateau. A study is underway to investigate if such a phenomenon is associated with the eastern boundary of the plateau.

Surface wave and seismic refraction data indicate that the crustal structure of the interior of the Colorado Plateau is typical of stable continental areas. However, Pn(upper mantle) velocities appear to be lower (8.0) than would be expected in a stable region. Thermal and gravity models of the plateau indicate the thickness of the lithosphere to be approximately 70km, a thickness which is intermediate between those of the Basin and Range and Great Plains. This thickness for the lithosphere is consistent with both seismic and electrical conductivity data and may explain the elevation difference between the plateau and the Great Plains.

Geophysical models of the deep structure of the Colorado Plateau suggest it is in a stage of uplift and heating. Zones of extension(rifting?) bounding the plateau appear to be growing at the expense of the more stable plateau crust.

HEAT FLOW AND PALEOSTRATIGRAPHY FOR THE EAST EUROPEAN PLATEAU

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Available heat flow data for plateau of the East European Plate (E. Eur. Pl.) are discussed. The Voronezh and Volga-Ural anticlines are characterized by heat flow of 50-55 mW/m^2 which are little higher than the low mean heat flow (35-50) mW/m^2) for the entire Pre-Cambrian E. Eur. Pl. The Variscan areas (Herzinean age) of the Stavropol, Simpheropol, Nevinominsk and Adigeisk plateau and uplifts are characterized by heat flow in the range of 50-80 mW/m^2. The maximum heat flow reaches 120 mW/m^2 in the Stavropol plateau where the asthenospheric bulge is assumed according to magneto-telluric survey. Altogether, the E. Eur. Pl. with its plateau is characterized by lower heat flow values and the colder earth's crust than the Central European Pl. from the west side and the Siverian Platform from the east side. Paleomagnetic and paleostratigraphy study give some evidence of the epeirogeny and changes of the position of E. Eur. Pl. from the low to middle latitudes in Silurian time in periods of Late Silurian, Middle Triassic and Post Miocene. A correlation between heat flow and epeirogeny is discussed.

CENOZOIC IGNEOUS ROCKS OF THE COLORADO PLATEAU

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Cenozoic igneous rocks of the Colorado Plateau range in age from Laramide to late Holocene. They span the compositional range from carbonatite-kimberlite to rhyolite; slightly undersaturated basalt is most abundant. The rocks are generally alkalic, with soda predominating over potash, although, locally, enrichment in potash is quite marked. In general, intrusive rocks are confined to the center of the Plateau and extrusive rocks are most abundant near its margins. The outline below summarizes available geologic, geochronologic, geochemical, petrologic, and isotopic data bearing on the distribution and origin of these rocks.

San Francisco volcanic field

Location: southwestern Plateau margin, north-central Arizona
Age: late Tertiary and Quaternary
Rocks: undersaturated basalts (82 per cent by volume), basaltic andesites (4 per cent), hornblende andesites (1 per cent), trachytes (1 per cent), dacites (9 per cent), rhyodacites (1 per cent), rhyolites (2 per cent, some peralkaline)
Suites: alkali basalt-trachyte; intermediate to silicic rocks with calc-alkalic affinities confined to five central complexes; most rocks consanguineous
$^{87}Sr/^{86}Sr$: 0.7034
Xenoliths: mafic and ultramafic fragments of crustal layered intrusions cognate to the volcanic field

White Mountains-Springerville volcanic field

Location: southern Plateau margin, eastern Arizona and western New Mexico
Age: Oligocene to late Pleistocene or Holocene
Rocks: basalt, trachybasalt, latite, trachyandesite, trachyte, rhyolite
Suite: alkalic
$^{87}Sr/^{86}Sr$: no data
Xenoliths: no data

Mogollon Plateau

Location: southern Plateau margin, southwestern New Mexico
Age: Oligocene to Pliocene
Rocks: basalt, andesite, rhyolite, silicic ignimbrites
Suites: calc-alkalic and alkali-calcic
$^{87}Sr/^{86}Sr$: no data
Xenoliths: lherzolite in Pliocene basalts

Moore, Richard B.

Mount Taylor

Location: southeastern Plateau margin, northwestern New Mexico
Age: Pliocene to Holocene
Rocks: alkali basalt, andesite, trachyte, dacite, rhyolite
Suites: alkali basalt-trachyte; calc-alkalic rocks in stratovolcano
$^{87}Sr/^{86}Sr$: 0.7048 for lavas, 0.7076 for ultramafic xenoliths
Xenoliths: mantle-derived ultramafic rocks in alkali basalts

Western Grand Canyon

Location: western Plateau margin, northwestern Arizona and southwestern Utah
Age: Pliocene to Holocene
Rocks: basanite to basaltic andesite
Suite: mildly alkalic
$^{87}Sr/^{86}Sr$: 0.7037
Xenoliths: mantle-derived ultramafic rocks

Marysvale

Location: northwestern Plateau margin, southwestern Utah
Age: Oligocene to Holocene
Rocks: sodic andesite, latite, quartz monzonite, rhyolite, alkali-olivine basalt
Suites: calc-alkalic and alkali-calcic
$^{87}Sr/^{86}Sr$: no data
Xenoliths: no data

Stocks and Laccoliths

Location: southwestern Utah (along possible northern tectonic boundary of Plateau); center of Plateau in southwestern Colorado, and northeastern Arizona
Ages: Laramide (Ute, Navajo, and Carrizo Mountains); Eocene (Henry Mountains); late Oligocene and early Miocene (Abajo and La Sal Mountains)
Rocks: chiefly diorite
Suite: alkali-calcic
$^{87}Sr/^{86}Sr$: no data
Xenoliths: chiefly amphibolites

Navajo-Hopi Province

Location: central part of Plateau in northeastern Arizona, northwestern New Mexico, and southeastern Utah
Ages: Navajo-late Oligocene and early Miocene; Hopi-Pliocene
Rocks: Navajo-chiefly potassic minette, minor kimberlite-carbonatite; Hopi-chiefly sodic limburgite and monchiquite, with local pods of

differentiated syenite
Suites: Navajo-strongly potassic; Hopi-sodic ultramafic
$^{87}Sr/^{86}Sr$: no data
Xenoliths: cumulate ultramafic rocks in Hopi field; mantle-derived ultramafic rocks in Navajo field

Available field and petrochemical data suggest that most igneous rocks on the Colorado Plateau were derived from the mantle; contamination by crustal material has been important only locally. Wide variations in compositions of mafic and ultramafic rocks suggest that 1) melting of mantle constituents occurred over a considerable depth interval, ranging from >40 to 200 km below the surface; 2) the mantle is heterogeneous, both laterally and vertically; 3) fractionation among various basaltic magmas may have been extensive; 4) areas enriched in CO_2 and H_2O are present in the mantle. The most reasonable parental material lies in the pyrolite-peridotite range; locally, eclogite may be abundant.

Extrusion of basalt, which volumetrically is dominant on the Plateau, has been related to the extensional tectonic regime which has prevailed during much of late Cenozoic time. Development of oversaturated intermediate to silicic magmas, whose eruptions commonly have been concentrated in a few centers (e.g., San Francisco Mountain, Mount Taylor, White Mountains), from undersaturated parental material may result from hydration of parts of the mantle or from local enlargement of the zone of partial melting to include areas where only the lowest-melting fraction of mantle material is withdrawn.

In addition to the structural evidence, the presence of kimberlitic rocks near the center of the Plateau suggests, by analogy with other stable areas, that the Plateau is a mini-craton. Igneous activity on the Plateau has been concentrated near major structural features, which provide the best access to the surface and presumably are the loci of pressure-release and perhaps hydration at mantle depths where magmas are generated. The scarcity of igneous rocks on the Plateau, in contrast to the Basin and Range Province to the west and south and the Rocky Mountains to the east, may be the result of a thicker, less easily penetrable, lithosphere under the Plateau. Basin and Range structural deformation and attendant igneous activity appear to be encroaching on the western parts of the Plateau as the North American plate moves westward.

TECTONIC HISTORY OF THE COLORADO PLATEAU MARGIN, DATE CREEK BASIN AND ADJACENT AREAS, WEST-CENTRAL ARIZONA. J. K. Otton and W. Earl Brooks, Jr., U. S. Geological Survey, Denver, Colorado 80225

The Date Creek Basin is situated at the eastern margin of the Basin and Range province adjacent to the transition zone between the Colorado Plateaus and Basin and Range in west-central Arizona. Northeast of the basin, the transition zone is underlain principally by Precambrian igneous and metasedimentary rocks with a cover of volcanic and sedimentary rocks of Oligocene through Pliocene age and of varying thickness. The older Tertiary rocks are largely andesites and latites of late Oligocene and early Miocene age, and the younger rocks are largely alkali basalts with interbedded, locally tuffaceous sedimentary rocks (McKee and Anderson, 1971).

To the west and southwest of the basin lies a complexly deformed terrane composed of Precambrian through Mesozoic metamorphic rocks and lower Miocene through Pliocene basin-fill sedimentary rocks and acidic to mafic volcanic rocks. The area is typical of the Basin and Range province to the north in that the basins are not bounded by northerly-trending master normal faults with great displacement, but rather the basins appear to have formed in downwarped sections of crust later modified by faulting of modest displacement.

The Date Creek Basin lies across the boundary between two structurally distinct areas. The changes in structure and stratigraphy are recorded in the basinal rocks, which are well exposed along the northern side of the basin.

The oldest Tertiary rocks exposed in the basin area are andesitic to rhyodacitic volcanics of probable late Oligocene to early Miocene age, which extend from the east end to the west-central part of the basin. In their easternmost exposures, the rocks are essentially flat-lying and unfaulted. To the west they are cut by northwest-trending normal faults that have progressively greater displacements of as much as 300 m. Dips to as much as 50° are observed in the tilted volcanic section. Greatest movement on these faults postdates the volcanic rocks, whose probable age is 26 to 20 m.y., but predates overlying rocks of the Chapin Wash Formation, dated at about 18 to 14 m.y. ago; therefore, the inception of Basin and Range-style faulting seems best placed at about 20 to 18 m.y. ago. Adjacent parts of the transitional zone were also the sites of late Oligocene to early Miocene intermediate volcanism (Sullivan Buttes latite, McKee and Anderson, 1971), but the first phase of Basin-and-Range crustal extension did not affect it.

Basins formed during the early stages of crustal extension were filled with thick sections of fluvial-lacustrine rocks, which were accompanied first by andesitic to rhyolitic volcanism and then by rhyolitic and basaltic volcanism. The rhyolitic volcanism provided tuffaceous debris to the lacustrine rocks and was the probable source for major uranium mineralization found in those rocks.

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Vertical tectonism, marked by gravity sliding, doming, and thrust faulting, occurred in pulses between 18 and 14 m.y. ago. This tectonism was most intense to the west of the Date Creek Basin, and the west end of the basin was strongly affected by the events. Previously deposited basinal sediments slid off a rising dome as loci of uplifts migrated. Metamorphic rocks, including metamorphosed Paleozoic sediments and a distinctive metavolcanic rock, were also shed off rising domes as monolithologic breccias or brecciated slide masses. The eastern end of the Date Creek Basin and the adjacent transition zone were apparently totally unaffected by the paroxysms in the Basin and Range. Facies relations in basinal sediments suggest that parts of the transition zone were high-standing and provided sediments periodically.

Following these early Miocene events, alkalic basaltic volcanism, accompanied locally by acidic volcanism and fluvial-lacustrine sedimentation, occurred throughout the Basin and Range (Eberly and Stanley, 1978; Otton, 1977) and the transition zone (Gomez, 1978; McKee and Anderson, 1971) of central and west-central Arizona. Ages of rocks of this period range from 14.5 to 10 m.y. These rocks were deposited on surfaces of low to modest relief. It seems likely that the Basin and Range and transition zone areas were approximately the same elevation at this time. Between 10 and 6 m.y. ago, a period of major normal faulting and folding affected the Basin and Range and adjacent parts of the transition zone. Movement on the Sandtrap Wash fault (Shackelford, 1977), which forms the southwestern boundary of the Date Creek Basin, and on a fault zone which goes up the Big Sandy River, probably occurred during this time period. The eastern end of the basin shows no evidence of faulting; however, the basinal sediments were probably gently tilted to the southwest. In the transition zone, major faulting occurred at this time (the Coyote and Verde Faults, other probable Miocene-Pliocene faults in Kirkland and Skull Valleys). The present topographic relief between the Basin and Range and the transition zone was probably established at this time.

The last 6 m.y. has been a period of relative tectonic stability during which exterior drainage was established. Small fluvial-lacustrine basins formed locally. Minor basaltic and acid volcanism occurred in the transition zone and in the Basin and Range (Suneson and Lucchita, 1978).

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V_p MEASUREMENTS ON CRUSTAL XENOLITHS FROM SAN JUAN COUNTY, UTAH, E.R. Padovani, J. Hall, and G. Simmons, Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

The P-wave velocity structure of the crust below the Colorado Plateau was interpreted by Roller [1] and re-interpreted by Prodehl [2] on the basis of Roller's data. See Table 1. Common to both models are (i) a mean velocity of 6.1 to 6.2 km/s in the upper crust, (ii) significant thicknesses of rock of mean velocity 6.7 to 6.8 km/s in the lower crust, and (iii) a low velocity (7.8 km/s) below the Mohorovicic discontinuity.

Table 1.
Crustal Models.

Roller (1965)			Prodehl (1970)			This Paper
Depth (km)	Velocity (km/s)	Comment	Depth (km)	Velocity (km/s)	Comment	Rock Types
0			0			
	6.2	constant velocity		6.1-6.2	constant velocity	granite
			7	6.1-6.2	mid-crustal gradient zone	mixed metamorphic and igneous
25		discontinuity				
	6.8		33	6.7-6.8		
		constant velocity	37		high gradient zone	mafic gneiss
42		Mohorovicic discontinuity	42-48---7.6-----transitional Mohorovicic discontinuity			
	7.8		47			
				7.8		

We have measured V_p on sets of orthogonal cores from crustal xenoliths obtained from Moses Rock dike and Mule's Ear diatreme. Measurements were made with the pulse transmission technique at room temperature as a function of confining pressure to 6 kb on dry cores. From these data, we have estimated velocities for *in situ* conditions. The accuracy is about 0.1 km/s. Details of rock types, grain densities, and estimates of the depth of origin and velocity are given in Table 2. V_p has been corrected for thermal effects with a coefficient of 1×10^{-4}°C^{-1} determined by Peselnick and Stewart [3] for a metagraywacke. We assumed a value of 20°C/km for the geothermal gradient. No length correction was made to the experimental data.

The presence of rocks in our collection of crustal xenoliths with the spread of velocities shown in Table 2 is considered to be good evidence for the general validity of Prodehl's model. In Table 1, we show our interpretation of his model in terms of most likely rock types.

V_p MEASUREMENTS ON CRUSTAL XENOLITHS

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Table 2.
Properties of Crustal Samples.

Sample #	Grain Density (gm/cm^3)	Wild Guess at Depth (±.5km)	P(kb)	V_p (km/s)	$\bar{V}_p$ (km/s)	Rock Type and Locality
1928 x	2.656	10(4)	3	6.12	6.15	granite, Moses Rock
y	2.658			6.14		
z	2.656			6.16		
1934 x	2.916	18	5.5	6.87	6.20	garnet-sillimanite gneiss, Mule's Ear
y	2.909			6.03		
z	2.929			5.73		
1941 x	2.932	15	4.5	6.37	6.40	pyroxene granulite, Moses Rock
y	2.944			6.35		
z	2.942			6.43		
1950 x	2.932	25	8	6.82	6.60	amphibolite, Moses Rock
y	2.944			6.58		
z	2.942			6.37		
1917 x	2.913	25	8	6.75	6.70	gneiss, Moses Rock
y	3.008			6.62		
z	3.007			6.68		
1929 x	3.162	35	10	6.42	6.45	garnet amphibolite, Mule's Ear
y	3.063			6.36		
z	3.197			6.51		

V_p values are rounded to nearest multiple of 0.05 km/s. The symbol z signifies propagation direction perpendicular to foliation, x and y parallel to foliation, with x parallel and y perpendicular to the lineation, if present, on the foliation surface.

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HYPOTHESIS TESTING FOR EVALUATION OF THE GEOTHERMAL RESOURCES OF NEVADA, J. Thomas Parr, The Analytic Sciences Corporation, Reading, Mass. 01867

A hypothesis testing methodology has been developed to enable the integration and joint evaluation of diverse data types. To test the technique a number of geophysical and geological data bases have been used to assess the probable occurrence of additional geothermal resources in the State of Nevada. Using known hot springs as evidence of existing geothermal anomalies, a multidimensional statistical signature of typical Basin and Range geothermal sources is calculated. This is compared point by point on an eight kilometer grid to a signature calculated for the entire state. A likelihood ratio, expressing the relative probability of existing geothermal resources, is calculated for each point on the grid and a map of these ratios is presented.

The signatures used for the calculations have been developed from over one hundred indices derived by prior interrogation of the source data bases. The latter have included an historical record of seismic events in the region, a file of LANDSAT linears in Nevada, a map of major crustal fracture zones also determined from LANDSAT imagery, and a digitized geological map of Nevada. Gravity, aeromagnetic and hydrogeochemical data, as well as most other information types, could be readily added, as they become available, for an improved estimate of the resource potential.

The technique developed is seen primarily as a tool for regional reconnaissance. Its application is particularly appropriate to the evaluation of resources for which the known correlation with measured parameters is weak. In this regard, uranium deposits as well as geothermal anomalies are of special interest.

"PLATEAU UPLIFT" IN ARIZONA--A CONCEPTUAL REVIEW. H.W. Peirce, Bureau of Geology and Mineral Technology, University of Arizona, Tucson, Arizona 85721; P.E. Damon, and M. Shafiqullah, Laboratory of Isotope Geochemistry, Dept. of Geosciences, University of Arizona, Tucson, Arizona 85721

Before we can evaluate the question of "Colorado Plateau uplift", we must first define it as a physiographic province. Classically, its boundaries have been considered to be the Uinta Mountains on the north, the Rocky Mountains on the east and the Basin and Range Province on the south and west. The Basin and Range Province experienced extensive episodic magmatism and deformation during the Mesozoic and Cenozoic. In contrast, igneous activity tended to bypass the Colorado Plateau except for scattered intrusions and marginal bimodal volcanic fields. The plateau strata are typically horizontal and relatively undeformed as compared to rocks of equivalent age in the Basin and Range Province. In this respect, the Colorado Plateau is similar to that part of the "gang-plank" of the western Great Plains in New Mexico, Colorado, Wyoming and Nebraska from which it is separated by the Rocky Mountains. In fact, on a longitudinal topographic profile of North America drawn from San Francisco east to the Mississippi River, the Colorado Plateau appears to be a continuation of the "gang-plank" beyond the Rocky Mountains, and western North America has a configuration that is very similar to that of the east flank of the East Pacific Rise (see figure). Furthermore, both the "gang-plank" and the Colorado Plateau have had similar histories. Both areas were within the Rocky Mountain Geosyncline and both areas were subject to uplift in post Turonian time. To concentrate solely on the "uplift" of the Colorado Plateau while ignoring the uplift of the much larger "gang-plank" and, indeed, all of western North America, is like "straining at a gnat while swallowing a camel".

During the Laramide Orogeny, the Colorado Plateau, along with the "gang-plank", was raised from below sea level to some unknown altitude above sea level and has remained above sea level since that time. In late Eocene time, it was part of a more extensive erosion surface and rivers flowed from the Basin and Range Province onto the Colorado Plateau in a general northeasterly to easterly direction (Lindgren et al., 1910; Schmitt, 1933; Mackin, 1960; Young and Brennan, 1974; Epis and Chapin, 1975). This drainage system was disrupted during post Eocene time by uplift of mountain ranges to the north and east and by rifting of the Basin and Range Province to the south and west.

Although broad generalizations such as those above can be made, much of the detailed history of the Colorado Plateau remains obscure. This is, in part, a result of semantic difficulties including a failure to ask the right questions. For example, the continued use of the expression "plateau uplift" appears to us to render a disservice to understanding the geologic history of Arizona. Can uplift of the Colorado Plateau in Arizona be isolated from uplift of a much broader region?

Although it is evident that Cretaceous marine sediments along the Mogollon Rim in Arizona have been raised to an elevation of 7000 feet above sea level, the timing and rate of post Cretaceous uplift cannot be clearly determined, and the total geographic area involved in the uplift is not obvious. Certainly there is no known boundary zone in Arizona along which such an uplift can be shown to have taken place, and this includes all of the popular southern

boundaries of the Colorado Plateau suggested by geologists up to this time.

Subsequent to the accumulation of upper Cretaceous marine deposits, seas withdrew from all of Arizona. Except near the Lower Colorado River, there are no post Cretaceous marine deposits in Arizona. The Laramide Orogeny was followed by development of an extensive erosional surface that now underlies Oligocene rocks both in the Basin and Range country and along portions of the Mogollon Rim. "Rim gravels" found on the Mogollon Rim were deposited by a river system flowing upon a surface that extended to higher country south of the present escarpment, a drainage that was entrenched at least 4000 feet into the general surface. At what elevation was the surrounding terrain at the cessation of entrenchment?

Following regional uplift, development of the erosion surface, and after an extensive episode of mid-Tertiary volcanism and related tectonism, the late Cenozoic Basin and Range disturbance radically changed the landscape over the southwestern half of the state. Although block faulting was extensive, the effect of this disturbance upon the elevation of the Plateau country of northern Arizona cannot be demonstrated. When multiple tectonic events are involved, it is difficult to apportion their respective influences on the modern landscape.

In summary, the concept of "Plateau uplift" in Arizona appears invalid because there is no recognized plateau that can be shown to have been exclusively uplifted as a separate entity relative to sea level. There is a portion of the Colorado Plateau in Arizona, but, its origin does not require "plateau uplift" in the explanation of its geologic history. However, it is clear that Basin and Range extension and rifting have disrupted older surfaces and drainage systems.

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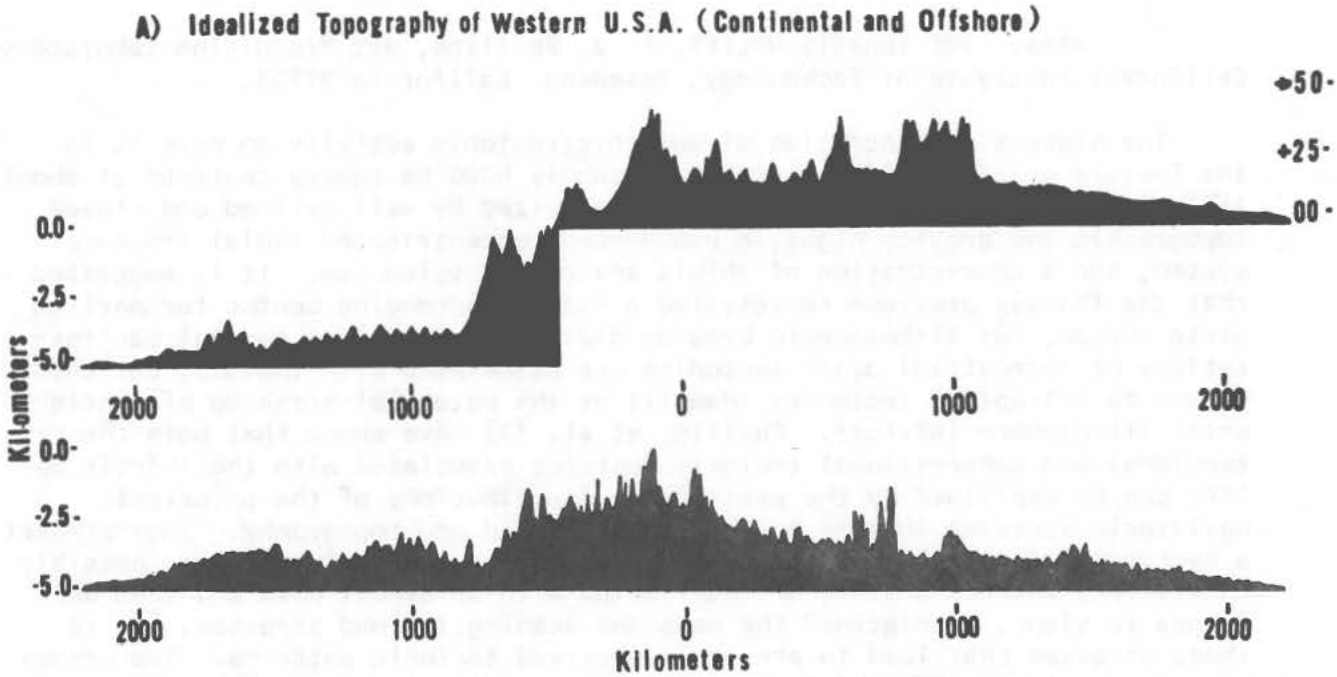

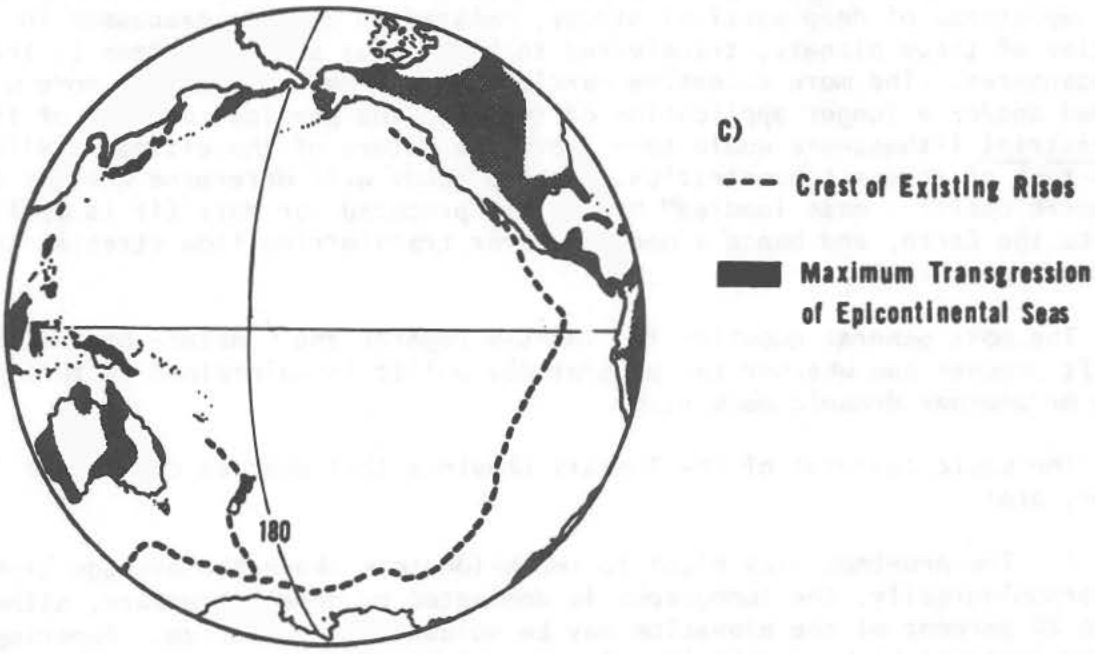

Oceanic and continental rises and the maximum transgression of Mesozoic-Cenozoic epicontinental seas (from Damon and Mauger, 1966).

MARS: THE THARSIS UPLIFT, R. J. Phillips, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91103.

The highest concentration of volcanic/tectonic activity on Mars is in the Tharsis uplift region, a province roughly 4000 km square centered at about 110°W longitude on the equator and characterized by well defined and closed topographic and gravity highs, a pronounced concentric and radial fracture system, and a concentration of shield and plains volcanism. It is suggested that the Tharsis province represented a nascent spreading center for martian plate motion, but lithospheric breakup did not occur. Thus several manifestations of terrestrial plate tectonics are associated with Tharsis, but these relate to intraplate tectonics (Hawaii) or the potential break up of continental lithosphere (Africa). Phillips et al. (1) have shown that both the tensional and compressional tectonic features associated with the Tharsis uplift can be explained by the present-day distributions of the principal deviatoric stresses imposed by the gravity field and topography. They present a hypothesis for the evolution of Tharsis wherein a dynamic process, possibly convection, reaches a state of equilibrium with an excess mass and then declines in vigor, "isolating" the mass and leading to load stresses. It is these stresses that lead to presently observed tectonic patterns. The excess mass may be in the form of igneous intrusive bodies in the crust and upper mantle.

Both the Tharsis fracture system and, for example, the radial system associated with the opening of the Atlantic during Triassic time (2) suggest the importance of deep vertical stress, related to dynamic processes in the mantles of these planets, transferred to horizontal stress systems in the lithospheres. The more extensive martian pattern may attest to a more widespread and/or a longer application of forces. The physical breakup of the terrestrial lithosphere would then imply the nature of the ultimate relief of this type of stress concentration. Future study will determine whether the "dynamic uplift - mass loading" hypothesis proposed for Mars (1) is applicable to the Earth, and hence a mechanism for transferring flow stresses to lithospheric breakup.

The most general question for Tharsis regards the nature of the Tharsis uplift process and whether the present-day uplift is maintained by this process or another dynamic mechanism.

The basic features of the Tharsis province that must be considered in any theory are:

1. The province lies eight to ten kilometers above the average globe. Geomorphologically, the topography is dominated by domal structure, although up to 20 percent of the elevation may be volcanic-constructive. Superimposed on the regional high are shield volcanoes, reaching heights of 25 km. A hydrostatic assumption implies the magma source region for the shield volcanoes is on the order of 250 km deep.

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2. A free-air gravity anomaly of 500 mgals exists over the Tharsis province, flanked by gravity lows of about -200 mgals in the adjacent lowlands of Chryse and Amazonis. The Bouguer anomaly has a minimum of -700 mgals over Tharsis.

3. The major surface units are shield volcanoes superimposed on a series of volcanic plains units, which are in turn superimposed on the ancient crust of the planet (see, e.g., 3). The Tharsis activity appears to have started over 2 billion years ago and continued to the present or recent past. The Tharsis fracture system predates most volcanic units and appears to have terminated early in the history of the volcanic deposition (4).

A number of scenarios have been advanced for the origin of the Tharsis province (5) and several involve a convective mechanism. Simple convection with viscosity independent of temperature and spatially homogeneous boundary conditions would appear to be ruled out. The major constraint appears to be the localization of Tharsis, implying a restricted convection pattern. If the first harmonic mode was dominant and Tharsis occurs at the single upwelling, then we might expect a negative gravity anomaly and a structural basin antipodal to Tharsis, both of which are not observed. If higher order convection was effective, then we might expect to see, instead of Tharsis, a number of smaller regions of positive gravity anomalies and doming.

When viscosity is a function of temperature, then the symmetry between upgoing and downgoing flow may be destroyed (see, for example, 6, Figs. 8-10). In particular, we would anticipate larger velocities and lower viscosities in a concentrated region of upwelling and a rather diffuse high viscosity, low velocity region of downwelling currents (7,8), leading to a weak antipodal effect.

Inhomogeneous boundary conditions may also have served to concentrate convection in one region of Mars. For example, the process of core formation by gravitational collapse of an iron-iron sulphide layer may release heat to the mantle in a spatially uneven pattern.

Another possibility for the uplift and maintenance of Tharsis involves an upper mantle inhomogeneity carrying anomalous heat sources and primordial in nature or arising from a buoyant instability in the lower mantle. This mechanism might account for the doming and early volcanism, but by itself might not sustain volcanism and support the uplift over geologic time.

The question of maintenance of the Tharsis gravity anomaly for perhaps 2 billion years could, however, involve convective mechanisms in the mantle. Tharsis must be supported by the finite strength of the interior or by a dynamic mechanism or both. Phillips et al. (1) have studied the question of finite strength maintenance of Tharsis and show that the anomaly, with dominant second and third spherical harmonic energy, would tend to be supported in the lower mantle. However, this is inconsistent with the volcanic

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activity observed and the expectation is that imposed shear stresses would rapidly decay from the deep interior, if indeed they ever existed at great depth. Finite strength support must ultimately be supplied by the lithosphere, and the question of stress levels depends mainly on elastic lithosphere thickness, which Phillips et al. estimate to be about 100 km. This value is based on thermal model considerations and on the location of certain tensional features postulated to result from lithospheric failure to shield volcano loads. According to an elastic model of partial Airy compensation (9) of the topography, the maximum deviatoric horizontal tensile stresses at the surface would be in the range 500 bars to 1 kbar. As discussed above, this stress system predicts the tensile and compressive features observed at the surface. At depth, maximum shear stresses research several kilobars and the question of whether these stress levels can be passively supported for several billion years is the key in a need to, as an alternative, invoke a dynamic mechanism to support Tharsis to the present.

Sleep and Phillips (10) have advanced a Pratt isostatic model for Tharsis, and while the stress levels due to this mechanism might be less, the base of the Pratt zone quite probably extends into the martian asthenosphere. Dynamic support would appear to be required to maintain this Pratt isostatic balance, in analogy to Watts' (11) dynamic mechanism proposed to support the Hawaiian swell.

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GEOTHERMAL CHARACTERISTICS OF THE COLORADO PLATEAU

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GEOTHERMAL CHARACTERISTICS OF THE COLORADO PLATEAU, Marshall Reiter, Arthur J. Mansure, and Charles Shearer, New Mexico Bureau of Mines and Mineral Resources & Geoscience Dept., New Mexico Institute of Mining and Technology, Socorro, NM 87801.

New heat flow measurements in the Colorado Plateau ranging in depth from 400 to 1900 m demonstrate that the heat flux throughout the region is 1.5 HFU and greater. Along the eastern and southern boundaries of the Plateau, near the San Juan volcanic field and the Mogollon slope respectively, high heat flows ($\gtrsim$ 2.2 HFU) are observed to intrude into the Plateau from 50 to 100 km. It is believed that the sources of these high heat flows are associated with the volcanics of the area and their sources. In the interior areas of the Plateau, away from the major volcanic phenomena along its boundary (e.g. the Black Mesa-Kaiparowitz synclinorium and the Four Corners area) heat flows are generally between 1.5 and 1.8 HFU, and appear to be rather uniform over large areas. This uniform heat flow characteristic over large areas of the interior Plateau suggests the lack of large scale, widespread, crustal thermal sources. It is possible that the lithospheric temperatures within the Colorado Plateau were once similar to the lithospheric temperatures within the Stable Interior. Present heat flow differences between the two provinces, implying different temperature distribution in the respective lithospheres, along with relatively uniform heat flows in the interior of these provinces, suggests asthenospheric differences which may relate in part to the uplifting of the Plateau.

RELATIONSHIP BETWEEN NONGEOSYNCLINE AND EPIGEOSYNCLINE UPLIFTS AND MOUNTAIN BUILDING. A. E. Shlesinger, Geological Institute of the Academy of Sciences, Moscow, USSR.

High mountains of the geological present and past may result from various origins. Some of them arise at the last stage of the geosyncline process (epigeosyncline mountain building). The others are independent of this process, and they are usually called "high plateaus" or "the regions of epiplatform activisation." The epigeosyncline mountain building is characterized by intense uplifts and granitic magmatic activity. Deep depressions compensating the uplifts are forming simultaneously. There is no magmatic activity in the foredeeps filled with mollasse deposits. Folding and faulting in the sediments in foredeeps are damped from their inner margins towards the outer ones. Inner depressions usually include subsequent volcanic rocks.

The nongeosyncline mountain building develops for a relatively short time, about several tens of millions of years in isolated regions. It took place on all the continents during the Devonian (mainly Early and Middle Devonian) and Late Cenozoic (mainly Neogene and Quarternary) time. The Mesozoic nongeosyncline mountain building is typical of the Pacific margin of Asia. The main portion of recent mountain regions resulted from nongeosyncline mountain building. Folding almost did not occur during the recent and old nongeosyncline mountain building. In contrast, block structures are typical of them.

The epigeosyncline and nongeosyncline mountain building may develop simultaneously or they may follow one another. The mountains developed in the Alpine geosynclines have likely been formed by horizontal compression, which is a cause of epigeosyncline mountain building. Then their altitudes have been strongly increased by nongeosyncline processes without folding.

The nongeosyncline mountain building usually occurs almost at the end of the geosyncline cycle or a little later. This implies one and the same source of energy for these processes. Nongeosyncline mountain building is more powerful. It forms mountains of higher altitude and of considerably greater areas. The epigeosyncline mountain building is of relatively local character.

Vertical movements in the epigeosyncline mountain building result from flow in the mantle. Strong folding occurred at the boundaries between high uplifts and depressions during their development. Basaltic magmatic activity is typical of nongeosyncline mountain building when the crust is under tensile stresses.

THE NATURE OF THE BASEMENT BENEATH THE COLORADO PLATEAU AND SOME IMPLICATIONS FOR PLATEAU UPLIFTS. Leon T. Silver, Div. Geol. and Plan. Sci., Calif. Inst. of Tech., Pasadena, CA 91109 and Thomas R. McGetchin, Lunar and Planet. Inst., 3303 NASA Road 1, Houston, TX 77058.

The nature of the preCambrian basement beneath the Colorado Plateau must be synthesized from patterns in the basement exposures on the plateau perimeter; from exposed cores of several interior uplifts; and from the accidental crystalline xenoliths ejected in scattered Cenozoic volcanic centers. Older (greater than 1400 million years) crystalline rocks are present beneath the Arizona, New Mexico, and Colorado portions of the Plateau. In Utah between the Colorado River and the Wasatch range it is not apparent that similar older crust is now present or ever was. Where known the basement is dominated by mafic and felsic igneous and metaigneous rock, both plutonic and volcanic. The subordinate metasedimentary type includes quartzites and less abundant pelitic schists. Excepting the southern San Juan basin, the basement apparently formed in two major episodes. A great middle Protorzoic eugeocyncline, orogen, and batholitic belt, northeast trending, formed in the interval 1700-1780 million years ago; this appears to be the primary continental crust and lithosphere-forming episode. Wide-spread alkalic-calcic batholiths were emplaced under anorogenic conditions in the interval 1420-1460 million years ago. The initial crust forming phase under the southern San Juan basin is probably slightly younger than elsewhere in the Plateau forming in the interval 1620-1700 million years ago. 1420 million year plutons are present there, also. Aside from sedimentation in shallow marginal marine and continental sedimentary basements in the late Protorozoic, the essential character of the basement was estimated in the interval 1400-1800 million years before the present.

The Tertiary events of the region have superimposed a metamorphic overprint on these rocks; this is particularly evident in the xenoliths contained within the kimberlites and alkalic basalts. A regional variation with increasing hydration from south to north across the southern edge of the Colorado Plateau is evident in the descriptions of the high rank mafic metamorphic xenoliths. At Kilbourne Hole, New Mexico, just off the Colorado Plateau, anhydrous two-pyroxene granulite and quartzofeldspathic gneisses are found (Padovani and Carter, 1977); at Green Knobs and Buell Park on the edge of the Plateau (Smith, 1977; Smith and Levy, 1976; Smith and Zientek, 1977) at Moses Rock and Mule Ear (McGetchin and Silver, 1972 and Helmstaedt and Schulze, 1977) abundant evidence for hydration of mafic granulite, eclogitic and ultramafic rocks is found, which probably occurred contemporaneously with the emplacement of the kimberlite and alkalic basalts in the mid-Tertiary. These observations strongly suggest deep seated hydration episode centered under the Colorado Plateau whose affects were less marked along the edges of the province. The uplift of the Colorado Plateau itself was less marked than the areas around its periphery. These surface events obviously reflect the deep-seated processes; the sequence of events <u>might</u> be directly attributable to re-equilibration of the thermal structure due to sesession of motion on a subduction zone in mid-Tertiary time.

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ECLOGITE AND HYDRATED PERIDOTITE INCLUSIONS IN VOLCANIC ROCKS ON THE COLORADO PLATEAU. Douglas Smith, Department of Geological Sciences, University of Texas, Austin, Texas 78712

Cenozoic volcanic rocks and inclusions of eclogite and peridotite within them yield information on the development of the crust and upper mantle of the Colorado Plateau. The eclogite and associated inclusions from Chino Valley, Arizona, and the eclogite and hydrated peridotite inclusions from the Navajo field are considered here.

The layered inclusions from Chino Valley (1, 2) occur in potassic latite; they have been interpreted as parts of a cumulate sequence, originally rich in eclogite, which re-equilibrated at temperatures of 700-950°C in the lower crust and uppermost mantle (1). New samples strengthen the hypothesis of a primary igneous origin for typical Chino Valley eclogites, but one inclusion is evidence that some gar-cpx rocks there are metasedimentary. One sample which supports an igneous origin contains layers of garnet plus orthopyroxene and of garnet plus clinopyroxene. Some of the gar-opx layers contain strained porphyroclasts of orthopyroxene with garnet lamellae. After garnet exsolution, all layers equilibrated at about 750°C, 13kb (gar-cpx Kd, 4-5; opx, 0.8-0.9% Al_2O_3, 0.1-0.2% CaO), conditions like those inferred for discrete eclogite nodules. Broad-beam electron probe analysis of an orthopyroxene porphyroclast with garnet lamellae (7.9% Al_2O_3; 2.0% CaO) suggests original orthopyroxene crystallization above 1100°C, however, and the interlayered eclogite must have experienced a similar history. In contrast, an apparent metasedimentary rock inclusion contains lenses of clinopyroxene-altered clinozoisite-garnet-amphibole-sphene in a matrix rich in quartz with subordinate clinozoisite(?) and garnet. Though the gar-cpx Kd's (8-12) are greater than those of typical Chino Valley inclusions, some other inclusions are similar in mineralogy to the lenses with clinopyroxene plus garnet, and such inclusions may also be derived from a metasedimentary sequence.

A single inclusion from felsic "minette" of the Navajo field at Mitten Rock is about 50% garnet, 35% jadeite-poor clinopyroxene, and 15% amphibole, with trace orthopyroxene (.8-1.3% Al_2O_3) and sodic andesine; the mineral assemblage indicates crustal granulite-facies metamorphism. The Mitten Rock inclusion and those at Chino Valley probably crystallized during the Precambrian, and such garnet-pyroxene rocks may be important constituents of the crust and upper mantle of many parts of the Plateau.

The low-temperature eclogite (e.g., 3, 4) and hydrated peridotite (e.g., 5, 6) inclusions in the Navajo kimberlitic diatremes formed later at lower geothermal gradients, and it has been suggested that they are fragments of a subducted slab (e.g., 4, 6, 7, 8). The subduction hypothesis has been supported by arguments that mineral zoning in the eclogites reflects equilibrium crystallization at increasing P and T (7, 8). Detailed electron probe traverses of minerals in a Garnet Ridge eclogite, however, show oscillatory zoning of pyrope vs almandine in garnet (Fig. 1) and of jadeite vs diopside in clinopyroxene (9). The oscillatory zoning reflects kinetic processes, and it indicates the importance of disequilibrium crystallization in these rocks. Pressure differences between core and rim crystallization of clinopyroxene have been calculated elsewhere (7) on the assumption of equilibrium with plagioclase plus quartz, but discontinuous zoning of Mg and Ca in garnet and of Ca, Fe, Mg, Al, and Cr in clinopyroxene is most likely due to changes in reacting assemblages; the assumption for calculation of pressure changes during crystallization is likely unwarranted. Uncertainties in calculated ratios of ferrous to ferric iron in clinopyroxene and phengite contribute large uncertainties to calculated temperatures. The hypothesis that these eclogites crystallized at constant pressure and

constant or decreasing temperature remains viable. It has also been suggested that the hydrated peridotite inclusions are fragments of subducted and metamorphosed ophiolite complexes (e.g., 6). Arguments against simple subduction hypotheses are that hydration affected both spinel peridotite and garnet peridotite, and that textures indicate retrograde hydration of originally anhydrous rock, not prograde metamorphism of hydrated peridotite. The low-temperature eclogites and hydrated peridotites thus may be fragments of altered continental mantle, not oceanic lithosphere emplaced at shallow depth beneath the Plateau. Even the former hypothesis, however, requires addition of water to the upper mantle beneath the Colorado Plateau in Cenozoic time. It is unclear whether peridotite hydration was only local, along deep fracture zones, or whether it occurred beneath large regions and could have influenced Plateau uplift.

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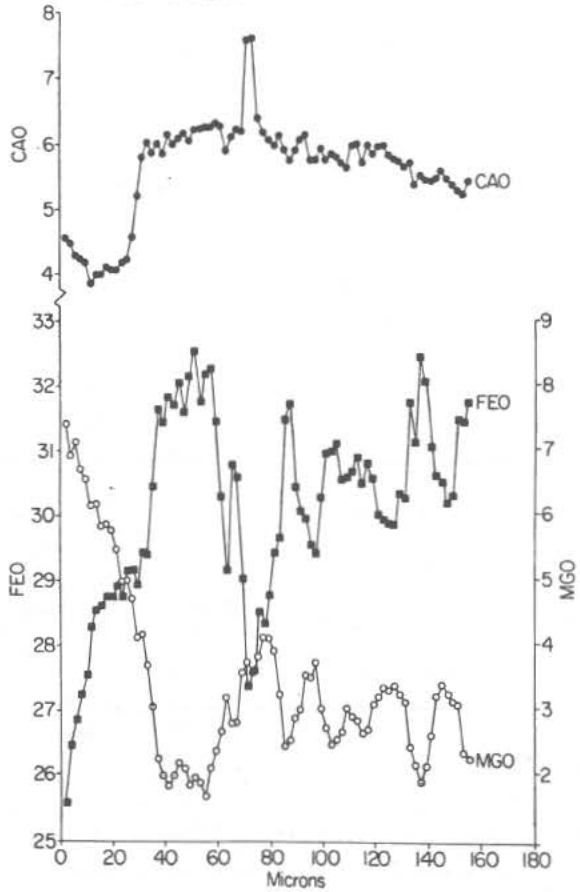

Figure 1: Results of an electron probe traverse across an intermediate region within a zoned garnet crystal in an eclogite from Garnet Ridge. Measurements were taken with a minimum beam diameter (1-2 microns) at 2 micron intervals. The traverse direction is perpendicular to planar, optically-visible growth lines. Note the antithetic variation of Fe and Mg. The oscillations are controlled by kinetics.

A Comparison of Crustal and Upper Mantle Features in Fennoscandia and the Rhenish Shield, two Areas of Recent Uplift

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Important parameters of vertical and horizontal movements of large areas are the creep properties of the asthenosphere and the lithosphere. The boundary between these two rheologically different units, however, is not well defined and has not yet been recognized by deep seismic soundings. The Mohorovicic-discontinuity (= Moho), on the other hand, which separates the chemically different crust and mantle, can well be traced, partly by reflection seismics (P_MP-Waves), partly by refraction seismics, (P_n-Waves), or by both methods.

In the Fennoscandian area and also in the Caledonides no P_MP - but strong P_n-waves have been detected in contrast to the observations within the Rhenish Shield where we find strong P_MP and sometimes intracrustal reflections, but only very weak P_n-waves (1.2). This basic difference between the two areas is certainly caused by two different velocity depth functions. These functions are strongly related to the different crustal depths and different temperatures. There are zones of enhanced reflectitity and zones of velocity reversals in the warmer and younger Rhenish Shield, especially near the Rhine Graben area, whereas a more gradual velocity increase down to the Moho is found in the colder Baltic Shield. Additionally, velocity reversals may be related to the quartz content of crustal rocks (3), whereas smooth transitions from garnet to eclogite could explain some features of the crust-mantle transition in Fennoscandia (4). In general, a high temperature of quartz-bearing rocks resulting in a low velocity lower crust should enhance the reflection coefficient at the Moho considerably. In fact, strong P_MP-waves are mostly found in warm areas. Missing P_n-waves also indicate a high temperature because the Moho may only consist of a small lid of high velocity with decreasing velocities below and permitting only weak head waves.

In Fennoscandia the Moho and the asthenosphere are considerably deeper than in the Rhenish Shield. It is suggested that the neighbourhood of the Atlantic Ocean with its much shallower and more pronounced asthenosphere is responsible for the asymetric uplift of Fennoscandia during the last 10^4 years (5). Stress patterns found in the crust indicate strong compressive

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stresses from the Atlantic Ocean to Fennoscandia (6). Creep movements from the lower viscosity oceanic asthenosphere entering the continental asthenosphere seem to be responsible (i) for the compressive stresses in the crust, (ii) for some of the uplift and (iii) for scraping off a probable former root of the Caledonides. The smaller Rhenish Shield, on the other hand, is influenced by compressive stresses from the Alps, and in its eastern part, which shows a kind of anti-root associated with a positive gravity anomaly, also by stresses from the opening of the lower Rhine Graben.

The Moho in the central part of the Fennoscandian uplift area (Bothnean Sea) shows a depression of about 5 km below a mean depth of 40 km as indicated by seismic refraction and gravity investigations (7,1). This depression cannot be explained by ice loading effects. It indicates an individual tectonic component in addition to the deglaciation effect of uplift in this area.

In general the tectonic stress pattern is strongly connected with the movement of asthenospheric material into the area of uplift. The reflectivity of the Moho, the ratio of P_MP-to P_n-amplitudes and the velocity depth structure in the lower crust and upper mantle provide clues to the temperature field at the appropriate depths. The topography of the Moho in connection with gravity data helps to trace zones of creep and uplift.

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GEOPHYSICS OF THE COLORADO PLATEAU. G.A. Thompson and M.L. Zoback, Department of Geophysics, Stanford University, Stanford, CA 94305

"I infer that the cause which elevates the land involves an expansion"
- Dutton, 1892

Dutton, who invented the word isostasy, was essentially correct about the Colorado Plateau (CP), as we now know from extensive gravity measurements, but this tells us little about the cause and mechanism of the uplift. Continental plateaus in general may be subduction-related as, for example, the Altiplano of South America, or non-subduction-related (perhaps hot-spot-related) as the plateau of East Africa. A considerable body of evidence indicates that the CP is subduction-related, even though subduction has ceased along most of the west coast of North America.

The Plateau is a relatively coherent block surrounded on three sides by the extensional, block-faulted, regime of the Basin and Range province (BRP) and Rio Grande Trough (RGT). The other boundaries are more diffuse - the whole region to the north and east (the Rockies) has been uplifted like the Plateau. In fact the Sierra Nevada, BRP, CP, and RGT appear to be parts of an inter-related system undergoing major uplift and deformation during the last 10-20 m.y.

The crust and upper mantle of the Plateau, based on sparse seismic refraction data, are intermediate in character between the BRP and southern Great Plains (Fig. 1). The major characteristics are: (1) a crustal thickness of about 40 km; (2) higher crustal velocities in the CP than in the BRP;

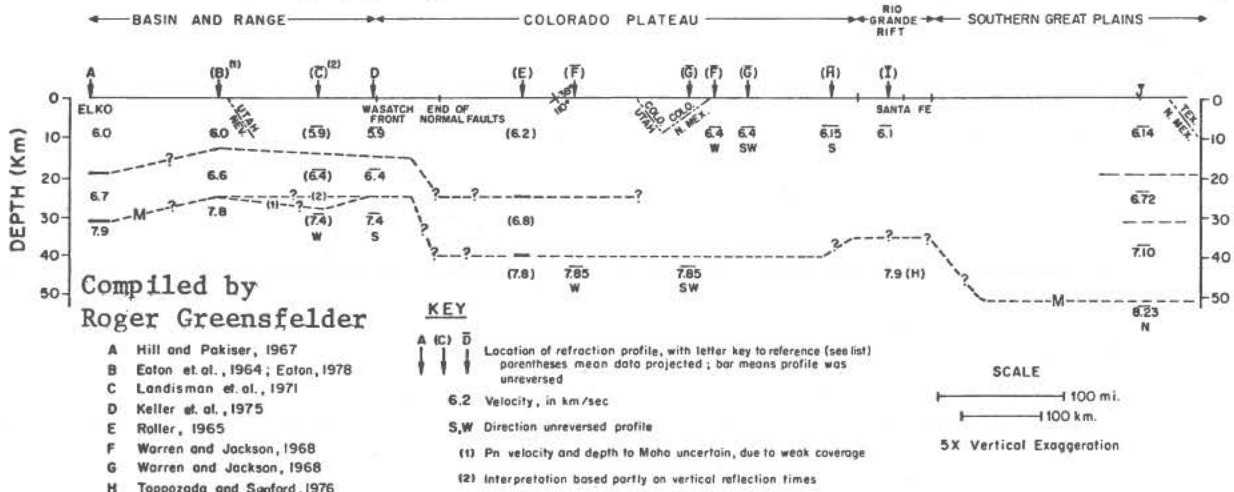


Figure 1. Seismic refraction crustal section from Elko, Nevada through Santa Fe, New Mexico

(3) an upper mantle velocity of about 7.8 km/sec. The P_n velocity is lowest (7.4 km/sec) in the eastern BRP and through a transition zone of the CP to the limits of normal faults that shred the western edge of the CP.

The mantle P-wave low velocity zone (LVZ), according to Archambeau et al (1969) is at greater depth and thinner in the CP than in the BRP, but other interpretations differ (Julian, 1970) and S-wave data are lacking. Taking the CP lithosphere thickness as 80 km from Archambeau et al, Porath (1971)

developed an electrical model of lithosphere over hot conductive asthenosphere (Fig. 2) based on magnetic variation anomalies. Compared to the CP, a thinner

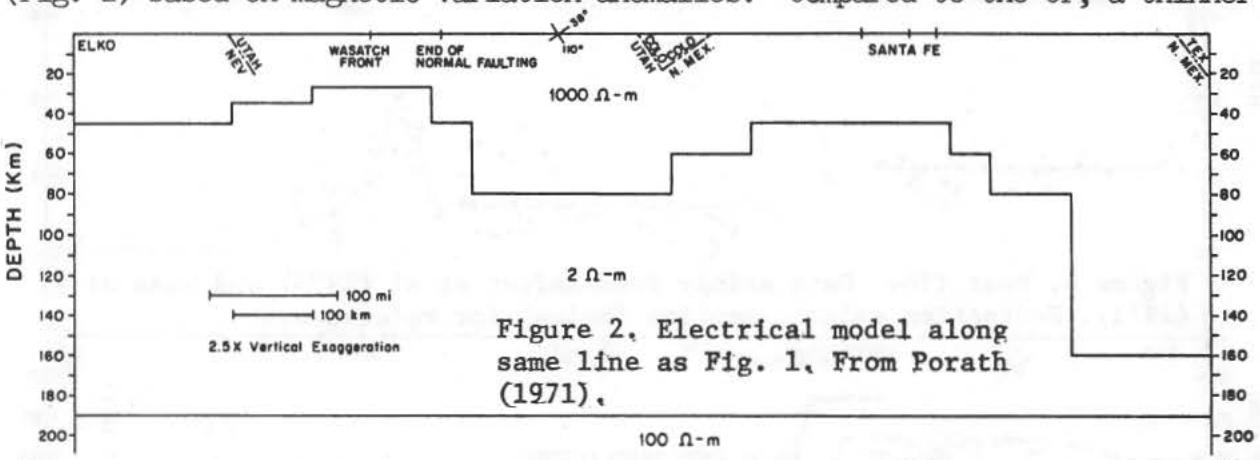
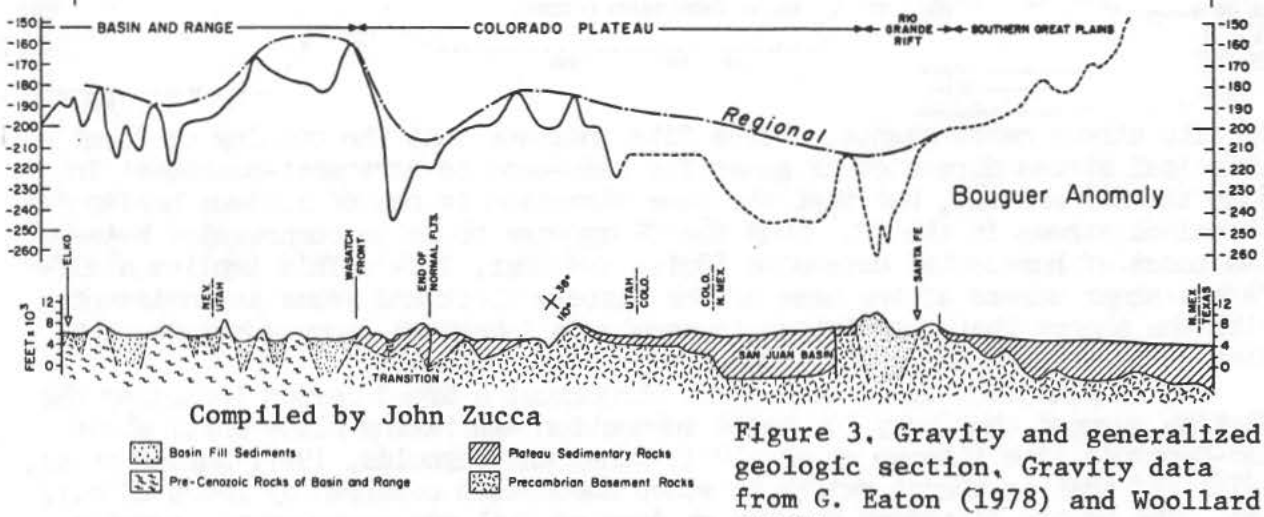


Figure 2. Electrical model along same line as Fig. 1. From Porath (1971).



Compiled by John Zucca

Basin Fill Sediments
Pre-Cenozoic Rocks of Basin and Range
Plateau Sedimentary Rocks
Precambrian Basement Rocks

Figure 3. Gravity and generalized geologic section. Gravity data from G. Eaton (1978) and Woollard (1964).

lithosphere is required in the BRP and a thicker lithosphere in the Southern Great Plains. In addition there are local anomalies due to exceptionally thin lithosphere at both the BRP and RGT margins of the Plateau. The Bouguer gravity data (Fig. 3), although complex in areas of low density sediments such as the RGT and basins of the BRP, seems also to reflect the regional variations in thickness of crust and lithosphere.

Heat flow in the CP (Fig. 4) is intermediate between the BRP (about 2 HFU excluding the Battle Mountain high and Eureka low) and the Southern Great Plains (about 1 HFU). Heat flow rises toward the RGT in the eastern 50 km of the CP, and a high heat flow seems to be characteristic of the southern margin of the CP as well. Shuey et al's (1973) analysis of long-wave length magnetic data to infer the Curie temperature depth along the western margin of the CP is consistent with the change in heat flow.

Three kinds of tectonic stress indicators are available for the BRP, CP and RGT. These are: (1) geologic indicators such as slip directions on faults and strike directions of dikes, (2) earthquake focal mechanisms, and (3)

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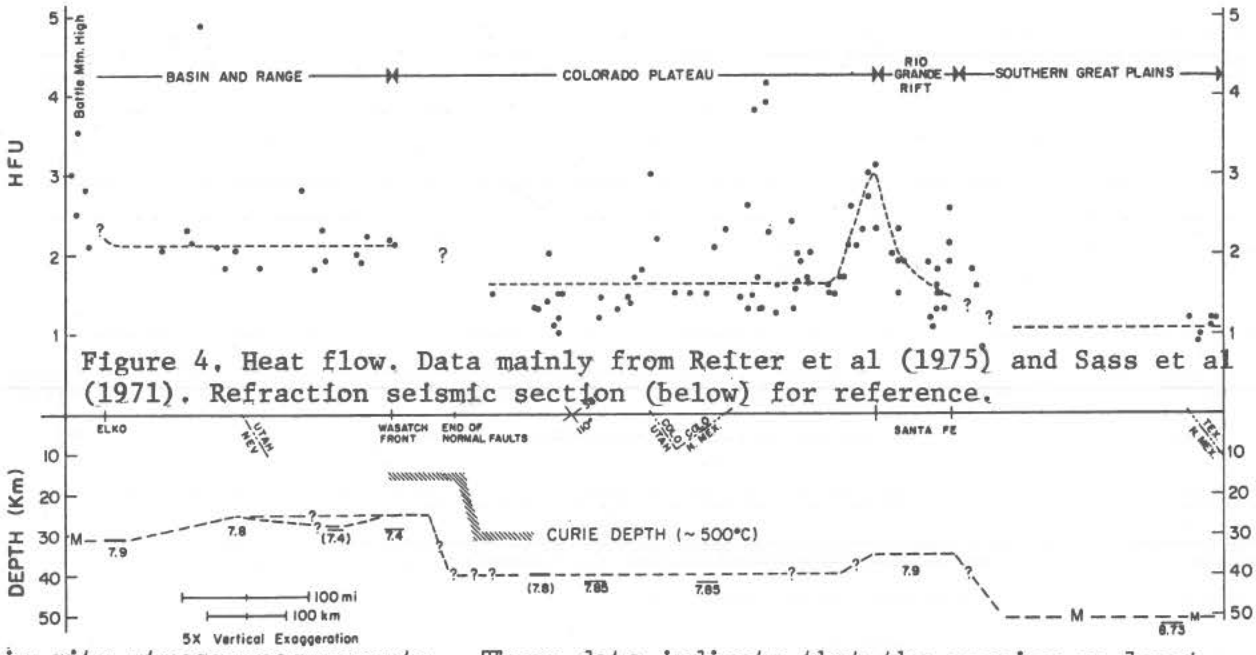

Figure 4. Heat flow. Data mainly from Reiter et al (1975) and Sass et al (1971). Refraction seismic section (below) for reference.

in situ stress measurements. These data indicate that the opening or least principal stress direction is generally west-east to northwest-southeast in both the BRP and RGT, but that the same direction is one of maximum horizontal principal stress in the CP. Thus the CP appears to be in compression between two zones of horizontal extension (Smith and Sbar, 1974). This implies a different shear stress at the base of the Plateau block and seems inconsistent with the theory that the Plateau is merely an inherited, more coherent, subplate subjected to the same stresses as its surroundings.

The compositions of igneous rocks throughout a broad region including the Plateau suggest that very low angle subduction was taking place until about mid-Cenozoic time (Lipman et al, 1971; Coney and Reynolds, 1977; Snyder et al, 1976) and that an abrupt switch to steep subduction occurred by about 20 m.y. ago. The Navajo diatremes brought up deep crustal and upper mantle samples including eclogite from beneath the Plateau 26-31 m.y. ago (McGetchen and Silver, 1972). These samples include hydrous rocks which Helmstaedt and Doig (1975) have interpreted as subducted oceanic lithosphere. Thus low-angle subduction may have been driving a cool plate under what is now the plateau at the time it was sampled by the diatremes 30 m.y. ago. We suggest that the stagnant shallow slab, cut off and left behind when subduction steepened, gradually warmed and expanded (with phase changes) to produce the regional uplift, confirming Dutton's inference in a way that he never suspected.

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THE ROLE OF EPIPLATFORM MOUNTAIN BUILDING IN THE DEVELOPMENT OF THE EARTH'S CRUST. A. L. Yanshin, Institute of Geology and Geophysics, Siberian Branch of the Academy of Sciences, Novosibirsk, U.S.S.R.

Many recent mountain regions arose on the platforms where the geosyncline process was terminated a long time ago. They are usually called "high plateaus" or "the regions of epiplatform activisation". The nongeosyncline mountain building takes place only in those platform regions which existed as relatively high platform shields, or in the areas where the Phanerozoic folded basement was covered only by a thin sedimentary layer. This process did not practically arise in the regions of deep sedimentary basins.

Epiplatform mountain building occurred several times in the past; however, it was different for various regions and for various geological epochs. Devonian depressions are widespread in the regions of the Baikalian and Caledonian folding. They are filled with mollasse deposits which should have been produced by the erosion of adjacent mountains. Similar depressions were formed at the Mesozoic time (from the Early Triassic till the Early Cretaceous) in the east of Asia. High uplifts and intense granitic magmatic activity were typical of the adjacent regions at that time.

Epiplatform mountain building is typical of the Late Cenozoic time. There are many regions where the formation of recent mountains was not accompained by folding. They all should be attributed to the above origin. Among them are the Altai-Sajany region, Baikal region, Vitim-Patom highland, Caledonian mountains of Norway, a number of mountain regions in Western Europe (Harz, Sacso-Turingicum and others). The formation of all these mountains was not associated with the preceding geosyncline development. The same is valid for the East-African rift zone.

The epiplatform mountain building creates a large contrast in relief (up to 10-15 km between positive and negative crustal displacements) with linear structures, which are usually of a block character. Compressional folding and thrusting often arise in mollasse deposits near the boundaries between high uplifts and depressions. Intense volcanism of a basic type takes place in many regions.

The epiplatform mountain systems resulted from intense differential vertical movements caused by strong heating of the underlying mantle. The influence of horizontal crustal movements should be taken into account for the formation of some structures, e. g., Tyan-Shan. It is likely that the epigeosyncline mountain building resulted from the same deep-seated mechanism as the nongeosyncline one.

NATURE OF CENOZOIC TECTONISM, VOLCANISM AND EROSION ALONG THE SOUTHWESTERN EDGE OF THE COLORADO PLATEAU IN ARIZONA. R.A. Young, Department of Geological Sciences, State University College of Arts and Sciences, Geneseo, NY 14454

The southwestern margin of the Colorado Plateau in Arizona records a distinctive sequence of deformational, erosional and volcanic events throughout much of Cenozoic time that appears to fit well into the regional geologic structural framework most recently summarized by Drewes (1) and Eberly and Stanley (2). The major plateau structures post-date the widespread early Tertiary erosion surface (3), which appears to have started to form in Paleocene time and has been little modified by Colorado River erosion.

A late Oligocene age for the earliest plateau marginal volcanism that covered this old surface has been documented by Young and McKee (3), but the northeast-flowing drainage had probably been disrupted earlier by structural deformation. Drewes (1) distinguishes between an early Tertiary (75 my) east-northeast compressional phase and a later (55 my) east-west compressional phase in the adjacent Cordilleran orogenic belt. The most recent period of compression may be related to the formation of three north-south trending monocline complexes which blocked early Tertiary drainage on the Hualapai Plateau.

Kelley (4) presents convincing evidence for the compressional origin of the other major monoclines throughout the plateau. It is noteworthy that all the Hualapai Plateau monoclinal flexures trend north-south whereas the younger normal faults trend either north-northwest or north-northeast. Wherever the individual monoclines on the Hualapai Plateau locally deviate from a north-south trend, they change abruptly into faults, generally recurved toward the northwest or southwest. Such features are suggestive of east-west compressional stresses related to the development of the early Tertiary Cordilleran orogenic features described by Drewes (1). The relatively minor effect of compressional stresses on the Hualapai Plateau can be attributed to the thin Paleozoic sedimentary cover present at the time of deformation and to the character of the Precambrian basement forming the plateau block.

None of the major Tertiary drainage channels shows any control <u>by</u> or obvious relation <u>to</u> the monoclines. In fact, the monoclines cut across or run parallel to major early Tertiary canyons in ways that demonstrate they could only have formed after erosion of the large channels. Where the largest monocline (Meriwhitica) crosses the large Tertiary channel in Milkweed Canyon, it produced a coarse, chaotic fanglomerate deposit that blocked the older canyon and produced thick limestone lakebeds on the upstream (southwest) side of the structure (5, 6). This marked the end of northeast through-flowing drainage in Milkweed Canyon. Considering the style of deformation now documented in areas adjacent to the plateau, it appears most reasonable to equate the early period of compressional tectonics with the late Paleocene to Eocene episode rather than the earlier Laramide events. Extensive erosion of the plateau margin had stripped it down to its present lower Paleozoic cover, and major drainages were through flowing prior to the major monocline deformation episode. Evidence for earlier Laramide volcanism and/or tectonic deformation is present along the lower Grand Wash Cliffs 30 miles south of the Colorado River. An eroded Laramide (65 my) pluton along the fault zone bounding the

plateau is unconformably overlain by Miocene volcanics, including the Peach Springs Tuff. This pluton undoubtedly fed a volcanic complex removed by the early Tertiary, pre-monoclinal erosion interval.

Erosional scarp retreat of the upper Paleozoic sedimentary sequence a minimum of 20 miles (32 km) across the Hualapai Plateau prior to monoclinal deformation is required to explain the elevation and east-west trend of the Tertiary channel through Hindu Canyon.

Logs of deep wells in Tertiary sediments at Peach Springs show the same general sequence of early Cenozoic deposits on the east side of the Peach Springs monocline as in Milkweed Canyon. The Peach Springs monocline blocked a narrow, west-flowing tributary canyon east of the old valley eroded along the Hurricane fault. A 300- to 400-foot thick limestone section within the buried sequence overlies several hundred feet of crystalline-bearing gravels. Coarse fanglomerates are present along the sides of the old canyon near the monocline. However, the lakebed sequence is absent in wells west of the monocline in the center of the prominent buried Tertiary channel along the Hurricane fault zone in the Truxton Valley. It can now be shown conclusively that the Truxton Valley-Peach Springs Canyon channel was a continuous northward-draining system.

If the early Tertiary monoclinal deformation does correlate with the compressional tectonics peaking near the end of Paleocene time (1), it precedes by almost 40 my the main displacement on the Hurricane fault and other plateau marginal faults south of the Colorado River. All these faults offset the Peach Springs Tuff (17 my), the Hurricane fault by the major portion of its displacement near Peach Springs.

There is evidence of substantially younger "thrust" or gravity glide structures in the Artillery Mountains (7) where lower Miocene volcanics (2) lie beneath older units. However, viewed in light of the regional geology, especially the onset of basin and range extensional tectonics and associated volcanism, these transported blocks may not represent the main episode of compressional tectonism observed throughout the general region. They might have developed as gravity structures during the transition from Eocene compressional tectonics to Miocene block faulting.

Other evidence supportive of a Paleocene age for the basal gravels and drainage on the Hualapai Plateau that was severed by the monoclinal deformation lies in the comparative degree of weathering of the clasts in the basal crystalline gravels compared to post-monoclinal (Eocene-Early Miocene?) gravels of similar lithologies, both of which underlie the Peach Springs Tuff. Disruption of the old regional drainage trending northeast through Peach Springs Canyon was followed by temporary reestablishment of similar local drainages into Peach Springs Canyon from Precambrian exposures along the plateau edge southwest of Truxton. Although both gravel units underlie the Peach Springs Tuff, clasts from the upper gravel appear as unweathered as those on modern fans, whereas the clasts from the older unit are so completely weathered that they disintegrate into clays and badly decomposed mineral fragments on removal from the outcrop (except for quartzite or highly silicic clasts). Even allowing for postulated climatic changes from early to middle Tertiary time, the basal gravel must be significantly older than the lithologically similar gravels deposited following monoclinal deformation but prior to middle

NATURE OF CENOZOIC TECTONISM

Young, R.A.

Miocene volcanism.

This suggested sequence of monoclinal drainage disruption would make the limestones on the Hualapai Plateau approximately correlative with the Paleocene-Eocene lacustrine sediments in Utah. Preliminary pollen data by L. A. Sirkin (Adelphi University) neither verify nor preclude such an age assignment. Sparse pollen from grasses and one from Pterocarya were found in three samples.

The much younger age of the monoclines relative to the initial uplift and earlier erosion cycle that produced northeast-flowing drainages on the plateau margin is also demonstrated by the geomorphic relation of the monoclines to the drainage. In both Peach Springs and Milkweed Canyons the monoclinal flexures clearly postdate complete development of a deeply incised regional drainage system on an extensively eroded plateau. Assuming the initial uplift to the west was early Laramide, it must follow that the monoclinal flexures formed after a lengthy interval of erosion, but prior to the Miocene volcanism.

The main episode of post-Laramide volcanism evident in the Tertiary section on the plateau edge from south of the Colorado River to Trout Creek (125 km) extended approximately from 25 my to 14 my ago (late Oligocene to middle Miocene). Most of the earliest volcanics crossed the edge of the modern plateau from the west. Significant local volcanic centers were in the Aquarius and Mohon Mountains near Trout Creek. Some minor volcanic vents were located along or near the plateau edge on the Hualapai Plateau, but in all cases where major fault traces intersect volcanic units, the most recent faulting is younger. However, early Tertiary and much older faulting are indicated by the pre-basin and range drainage disruption, the localization of intrusives along the plateau margin, and the distribution of localized bands of foliated (sheared?) Precambrian rocks which parallel the plateau edge and part of the Hurricane fault trace. The Hualapai Valley contains a section of sediments and salt deposits to a depth of 5,995 feet (1800 m) south of Red Lake in an area formerly covered by Peach Springs Tuff. The lack of volcanic rocks in this well documents a post-middle-Miocene fault displacement of at least this amount along the plateau edge. Seismic and gravity data suggest that basement or volcanic rocks are at a depth of 12,000 feet near the center of the valley (8).

The geologic relations demonstrate: (1) Laramide tectonism and volcanism, (2) early Tertiary erosion followed by late Paleocene(?) to Eocene(?) compression, (3) Oligocene to late Miocene volcanism, (4) post-middle Miocene block faulting, and (5) late Miocene to Pliocene interior basin deposition, followed by Colorado River development. (new K-Ar Ages courtesy E. H. McKee)

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ON GEODYNAMICS OF CENOZOIC UPLIFTS IN CENTRAL ASIA

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High mountain ranges and plateaus of Central Asia are bright manifestations of intraplate tectonics. The majority of the uplifts strike roughly SE-NW or sublatitudinally. The presence of thrusts, reversed and strike-slip faults, as well as mechanisms of recent earthquake foci indicate that the uplifts were formed in conditions of compression having a NE orientation.

In eastern Central Asia the uplifts strike SW-NE. The Baikal arch ranks among them, rift depressions being confined to its axial part. To judge by the presence of normal faults and mechanisms of earthquake foci, the Baikal Rift Zone was initiated as a result of extension oriented across its structures.

The hypothesis of P.Molnar and P.Tapponnier on mechanic inhomogeneity of the lithosphere in Asia and on Cenozoic structures being a result of the pressure of the Indian Plate against the Eurasian Plate looks suitable for explanation of the nature of the uplifts having SE-NW and sublatitudinal strikes. However, these authors do not take into account the structure of the mantle.

It is established via seismic methods that the upper mantle below the Baikal arch, Tien Shan and Tibet (other uplifts are not studied in this respect) possesses some anomalous properties: lowered rate and higher consumption of seismic waves. The density of the anomalous mantle is lowered, since its upper portion takes part in realization of approximate isostatic balance,which is characteristic of the uplifts of Central Asia.

All the physical properties mentioned above are characteristic of the asthenosphere. That is why we can presume that the asthenospheric material below the uplifts intrudes into the lithosphere and rises to the bottom of the crust, i.e. the lithosphere becomes thinner and therefore deforms easier in compressional conditions. If the structures strike in parallel to the compressional vector, the substance of the gigantic asthenospheric diapir flows in horizontal direction and generates crustal extension resulting in rifting.

Nevertheless, the inhomogeneities of the mantle do not resolve themselves into variations in the lithospheric thickness.

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The anomalous properties of the mantle below the Baikal arch and Tien Shan range are followed to depths of 400 and 200 km, respectively, i.e. the asthenosphere itself is non-uniform. Difference in densities of the normal and anomalous asthenosphere below the Baikal Rift Zone is estimated at 0.005 g/cm^3. Such inhomogeneities in this layer cannot exist for a long time without a constant inflow as a result of gravitational convection of lighter (and, possibly, more heated) material from great depths. Arriving from below such substance is redistributed in the asthenosphere by flows and rises into the upswells of its roof.

Thus, we believe that the SW-NE oriented compression alone cannot generate all the Cenozoic crustal structures in Central Asia. Such a compression must go together with the uprise from the depth of heated material which alters the structure of the mantle.

FIELD TRIP GUIDE

GEOLOGIC BOAT AND ROAD LOG FOR PLATEAU UPLIFTS CONFERENCE
LAS VEGAS, NEVADA TO FLAGSTAFF, ARIZONA

ORIGIN: Boulder Beach, Lake Mead, Nevada

LAKE MEAD:

50 to 60 mile launch trip to view geologic features shown on Map 1. Emphasis of discussion will be timing, nature, and significance of Tertiary deformation along Colorado Plateau-Basin and Range boundary.

GENERAL SETTING:

North of the prominent strike-slip faults (Map 1) the Tertiary geology is characterized by sedimentary basin deposits, whereas south of the strike-slip faults Tertiary volcanism, faulting and uplift predominate. A significant portion of the volcanism was centered around 14 my ago,and much of the structural deformation occurred since 11 my ago (Anderson et al., 1972). The Muddy Creek Formation is generally much less deformed than older Tertiary rocks and appears to span the time interval from 6 to 11 my ago. The Colorado River was established by 3.8 my ago, by which time the major portion of its valley had been eroded (Damon et al., 1978). It is generally accepted that the Colorado River did not flow through this region while Muddy Creek sediments were accumulating.

LAKE MEAD TRIP ROUTE:

In the western Lake Mead region the geologic relationships demonstrated at the Hamblin-Cleopatra volcano, Fortification Hill, and the northern Black Mountains will be described by Bob Bohannon, Paul Damon, Gene Shoemaker, and Ivo Lucchitta with additions by other participants familiar with various aspects of the geology.

From Middle Point to Hualapai Bay (Map 1) the reconnaissance geologic maps by Bob Laney (U.S.G.S., Phoenix) of the south shore of Lake Mead will be available for examination. This mapping indicates gravels of early Colorado River age were deposited by a south-flowing stream in the vicinity of Temple Bar. These gravels can be traced at elevations up to 2200 feet for six miles south of the present lake shore.

In eastern Lake Mead (Gregg's Basin and Iceberg Canyon) Ivo Lucchitta and Paul Damon will comment on the geology and the significance of new ages determined for volcanic flows pertinent to the origin of the Colorado River.

The Lake Mead portion of the trip will be completed with a short trip by bus from South Cove to the north end of Grapevine Mesa for a spectacular view of the geology and discussions of critical relationships mapped by Ivo Lucchitta. Enlarged oblique and vertical aerial photography and satellite imagery will be

used to illustrate the geology of adjacent areas not accessible during the launch trip.

The bus will proceed 25 miles south from the Grapevine Mesa overlook on the Pierce Ferry Road to the road running south through the Hualapai Valley (Map 2). Tertiary sediments and structures in the region will be described by Ivo Lucchitta.

HUALAPAI VALLEY-KINGMAN ROUTE:

0-17 miles

From the northern end of the Hualapai Valley the bus route runs southeast for 17 miles to the Clay Springs Road turnoff. Along this valley views of the northern Cerbat Mountains, Hualapai Plateau, Red Lake Playa, and Table Mountain can be seen. The southern end of Red Lake lies near a line connecting the northernmost remnants of Peach Springs Tuff in the Cerbats and on the Hualapai Plateau (locations 2, 3; Map 2). Six miles northwest of Red Lake a seismic profile indicates bedrock may be at a depth of 4400 feet below the surface of the valley. South of Red Lake three deep wells (Map 2; locations 12, 13a, 13b) indicate an alluvial valley fill of about 1800 feet with halite present down to the bottom of the deepest well at 5994 feet below the surface. The water table slopes northward beneath Red Lake and is at a depth of approximately 450 feet in the wells south of Red Lake.

17-35 miles

At the Clay Springs Road intersection the bus may turn 3 or 4 miles northeastward to obtain a better view of the Clay Springs pluton recently dated at 65± 3.5 my (McKee, 1978). This pluton (Map 2, location 4) is unconformably overlain by Miocene volcanics and demonstrates the early Tertiary age of the erosion interval which is represented by the surface of the Hualapai Plateau.

Proceeding southward toward Highway 66, the route provides views of the southern Grand Wash Cliffs. The conspicuous lack of obvious fault traces is significant, when compared to the faulting in ranges on the west side of the valley. Prominent lineaments in the Precambrian rocks appear to be contacts between granite and foliated rocks. This same relation appears to continue southward as far as Interstate 40. It is suggested that these contacts may mark zones of long-term shearing along the plateau margin.

The early Tertiary channel through Milkweed Canyon (Map 2, location 8) is clearly visible from the Hualapai Valley. Although smaller than the Truxton Valley channel along the Hurricane fault zone, the Milkweed channel is better exposed and better defined by surface and subsurface data. The major through-flowing drainage was disrupted by deformation along the Meriwhitica monocline.

A similar channel opposite the north end of the Peacock Mountains (Map 2, location 14) trends eastward into the Truxton Valley north of Highway 66. This

channel is also capped by Miocene volcanics, but its base is not well exposed at the edge of the plateau. Its precise trend into the Truxton Valley cannot be determined, but it may be a more significant channel than the more recently excavated valley where Highway 66 is located. The base of the Precambrian is lower in some places north of Highway 66, and only Tertiary gravels are exposed at the base of some canyons which have cut into the old channel. Shallow subsurface data are available for 5 wells (locations 30-34) at the southern end of the Hualapai Valley. The important relations are noted in the "Points of Interest" for Map 2.

Highway 66 to Kingman

Time and daylight permitting, the structure and distribution of Peach Springs Tuff outcrops from the west side of the Peacock Mountains to northwest of Kingman will be viewed prior to stopping at the Holiday Inn in Kingman.

Maps and aerial photographs of the areas covered will be available at the buffet dinner. Bob Littleton has prepared a slide selection of aerial views of the Lake Mead-Hualapai Plateau region.

ROAD LOG, DAY 2, KINGMAN TO FLAGSTAFF:

0-32 miles

After viewing the general structure of the Kingman area, several stops will be made between the northern Peacock Mountains and the edge of the plateau. Post-middle Miocene fault displacement of at least 1000 feet has occurred near Hackberry. The approximate location of the main(?) fault is near the intersection of the road running down the Big Sandy with Highway 66. From Highway 66 west of Hackberry, Slate Mountain (location 18, Map 2) can be seen. This feature is the metaconglomerate zone representing the intersection of the Hurricane fault trend with the plateau margin.

32-41 miles

The route of Highway 66 from Hackberry to Truxton contains excellent exposures of the Precambrian basement in the tributary channels of buried valleys sloping northeastward into the Truxton Valley. The relationships of flows, channels, and Tertiary gravels are best exposed on the south side of Highway 66. Upon reaching the region where the Miocene volcanics are covered by the alluvium and gravels of the Truxton Valley, minor faults in the Peach Springs Tuff are visible adjacent to the highway. The Peach Springs Tuff is present at a depth of 233 to 271 feet at Truxton (elevation 4390 feet). Approximately 1.5 miles east of Truxton a well penetrated granite bedrock at a depth of 615 feet (surface elevation 4420), and Peach Springs Tuff is tentatively located at a depth of 374 to 404 feet (locations 37, 19; Map 2).

From a point west of Truxton general views of the Truxton Valley, the Hurricane fault trace, Slate Mountain, and Peach Springs Canyon will be used to orient the participants for subsequent stops.

41-50 miles

Returning to Valentine, the bus will stop at the Hunt Ranch (site of geothermal well, location 17, Map 2) for a climb to the bluffs of Peach Springs Tuff south of Highway 66 (location 16, Map 2). A number of important relationships from the Peacock Mountains to Peach Springs and southward to the edge of the Truxton Valley can be illustrated from this vantage point.

50-107 miles

After lunch, the bus will return to Interstate 40 near Kingman for the trip through the southern Peacock Mountains into the upper Big Sandy basin. The view into the Aquarius Mountains from this route is superior to that obtained by driving parallel to the plateau edge. Features in the Knight Creek basin area (locations 22-26, Map 2) will be viewed and discussed from various vantage points.

107-157 miles

Precambrian rocks at the edge of the plateau are well exposed in the Interstate 40 deep cuts north of the Aquarius Mountains. Oligocene to Miocene volcanics cap the eroded Precambrian surface, which still contains scattered remnants of Cambrian sedimentary rocks. Fifteen to twenty interesting road cuts between the plateau margin and Seligman illustrate structural and stratigraphic relations not well shown on the geologic map of Arizona. Gary Fuis, who has done detailed mapping in the Fort Rock area (just east of the border of Map 2), will accompany the group to discuss significant features along the route. Several other individuals on the trip have done mapping in this region for private corporations and government agencies. A stop at the Fort Rock Ranch is tentatively planned.

The oldest Tertiary volcanic flows are basalts located 3 miles south of location 26 (Map 2) dated as 24.9± 0.9 my. The Aquarius Mountains volcanic center underwent its major eruptive activity between 17 and 18.2± 1.5 my ago. All these volcanics were erupted following extensive erosion of the region and deposition of early Tertiary gravels by north to northeast-flowing drainage from west and south of the present plateau margin.

Near Seligman, Gene Shoemaker will comment on the geologic features in the vicinity of the Aubrey Valley region (not shown on Map 2).

During the return to Flagstaff (90 miles) other participants may comment on the ages of volcanics and structural features along the route.

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EXPLANATION - GEOLOGIC MAP 1

Q	Quaternary alluvium
QT	Quaternary and Tertiary sediments undifferentiated. Includes alluvium, fanglomerate, Colorado River gravels, Chemehuevi Formation (generally of Pliocene and Pleistocene age).
Tmc	Muddy Creek Formation (dots)
Th	Horse Springs Formation
Ts	Tertiary sediments undifferentiated (may include minor volcanic units)
Tb	Younger volcanic flows of Grand Wash area (black). Mainly Pliocene.
Tvm	Volcanic flows within the Muddy Creek Formation (Pliocene to Miocene?).
Thv	Volcanics of Hamblin-Cleopatra volcano (generally Miocene).
Tv	Tertiary volcanics undifferentiated (generally Pliocene to Miocene).
M	Mesozoic rocks
P	Paleozoic rocks
Tp€	Precambrian rocks with numerous Tertiary dikes and plutons (Triangles).
p€	Precambrian rocks (Triangles).

Map Sources: Anderson et al., 1972
Anderson, R.E., 1973
Lucchitta, I., 1966
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GEOLOGIC MAP 1

Points of Interest, Geologic Features, and Geographic Locations

1. Fortification Hill (lowest basalt overlying Muddy Creek, 5.88± 0.18 my, Damon et al., 1978).

2. Calville Mesa (basalt, 11.1 my, Anderson et al., 1972). Rests unconformably on tilted and beveled upper Tertiary strata.

3. Hamblin-Cleopatra volcano (andesite, 12.7 my, Anderson et al., 1972).

4. Offset portion of Hamblin-Cleopatra volcano on Hamblin Bay fault (offset 12 miles between 12.7 and 11.1 my), total offset 65 km.

5. Horse Springs Tuff (15.3 my, Anderson et al., 1972).

6. Horse Springs basalt (13.2 my, Anderson et al., 1972).

7,8. Horse Springs Formation (14.9, 15.1 my, Fleck, 1970). (also southeastern projection of Las Vegas shear zone.)

9. Mt. Davis volcanics (range 11.5-15 my, 9 dates, Anderson et al., 1972).

10. Tertiary intrusives in Wilson Ridge (Precambrian) Ages 15.1, 13.6 my.

11. Fortification basalt in Muddy Creek Formation (Five dates, 3.7-5.2 my).

12. Boulder Beach

13. Calville Bay

14. Hamblin Bay

15. Hoover Dam

16. Bonelli Bay

17. Middle Point

18. East Point

19. Overton Arm, Lake Mead

20. Temple Bar

21. Temple Bay

22. Gold Butte

23. Virgin Canyon, Lake Mead

24. Hiller Mts.

25. Greggs Basin

26. Sandy Point (Basalt flow overlying Colorado River gravels and under Chemehuevi equivalent, 3.79± 0.46 my for 2 analyses, Damon et al., 1978).

27. South Cove landing point.

28. Grand Wash Bay-Cormorant Cliffs area (Basalt flow on Muddy Creek and Colorado River gravels, 3.80± 0.11 my for two analyses, Damon et al., 1978).

29. Wheeler Ridge, faulted Paleozoic rocks.

30. Iceberg Canyon, Lake Mead.

31. Pierce Ferry

32. Iceberg Ridge

33. Grapevine Mesa, Airport Point Overlook

34. Hualapai Bay

35. Snap Point (lavas)

36. Grand Wash Cliffs

37. Grapevine Wash

38. Pigeon Wash

39. Pinto Valley

40. Bonelli Peak

41. Grand Wash

EXPLANATION - GEOLOGIC MAP 2

Q	Quaternary alluvium
QT	Quaternary-Tertiary valley fill
Tmc	Muddy Creek Formation (dots) (Pliocene-Miocene)
Tv	Tertiary volcanics undifferentiated (mainly Miocene)
Tp,*	Peach Springs Tuff (small exposures interbedded with other flows also noted by asterisk symbol)
Ta	Flows, breccias, and tuffs of Aquarius Mts.
Ti	Tertiary intrusives (Laramide to Miocene age)
Tb	Basalt flows at base of Aquarius Mts. section (Miocene)
Tvs	Interbedded Tertiary volcanics and sediments undifferentiated (Paleocene? to Pliocene)
Ts	Tertiary sediments undifferentiated (Paleocene? to Pliocene)
P	Paleozoic rocks (horizontal line pattern)
p€	Precambrian (Triangles)

Map Sources:
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GEOLOGIC MAP 2

Points of Interest, Geologic Features and Geographic Locations

1. Red Lake Playa (elev. 2754 feet).

2. Northernmost Peach Springs Tuff outcrop in Cerbat Mts.

3. Northern most Peach Springs Tuff outcrop on Hualapai Plateau.

4. Laramide pluton (65.5± 3.5 my, McKee, 1978).
   Unconformably overlain by Miocene volcanics.

5. Intersection of Clay Springs Road

6. Cerbat Mts. (elev. 6900 feet)

7. Long Mt. (elev. 4352 feet)

8. Exposure of Tertiary channel at west end of Milkweed Canyon.

9. Locality for Peach Springs Tuff date, Damon, 1964.

10. Westwater well #1. Penetrated volcanics and sediments to depth of 462.5 feet from surface elev. of approx. 4850. Did not penetrate bedrock due to problems with caving of hole.

11. Outlier of Miocene volcanics capping Tertiary gravels derived from north of Colorado River. Adjacent to Separation Canyon fault.

12. Deep well drilled by Leonard Neal. Typical section in this portion of valley from surface: 400 feet of clay, 1100 feet of alluvium, 200 feet of "blue shale," 50 feet of anhydrite, salt (to depth of at least 5994). Well depth 1850 feet.

13a. Kerr-McGee #1 well (Red Lake Potash).
   Depth 2608 feet from 2788 surface, bottom in salt.

13b. El Paso Natural Gas #1 well.
   Valley fill 0-1796 feet, Salt 1796-5994 (bottom of hole).
   Surface elev. 2804 feet.

14. Peacock Mts. (fault scarps appear younger than those along plateau margin).

15,16. Peach Springs Tuff outcrops offset by 1000 feet.

17. Hunt Ranch (site of geothermal well drilled in 1978).

18. Slate Mountain. Nearly vertically dipping metaconglomerate zone presumed to be southern extension of Hurricane fault.

19. Indian Health Service well (1976). Surface elev. 4420 feet. Contact with granite is at 615 feet below surface. Volcanic section from 374 to 408 feet. Two miles west of Hurricane fault trace. Demonstrates bedrock slope to northeast into Peach Springs Canyon.

20. Location of 6 deep wells (836 to 1013 feet deep) drilled by the Santa Fe Railroad from 1903 to 1925. Comparison of existing well logs indicates well field is along extension of Peach Springs Monocline in deeply-incised tributary to valley along Hurricane fault. Generalized composite section shows approximately 200 feet of coarse alluvium over 400 feet of white (freshwater) limestone. The limestone is underlain by about 400 feet of quartzite-bearing gravels probably related to similar gravels further east in the Chino Valley. Surface elevation is 4800 feet; granite contact is at 3797 elev. and may be overlain by 70 to 100 feet of irregularly eroded Tapeats Sandstone.

21. Offset of Peach Springs Tuff along Hurricane fault in Peach Springs Canyon (200 feet).

22. Austin Peak pluton, intrusive from Aquarius Mt. volcanic center located at 23.

23. Intrusive in center of Aquarius Mts. Age constraints of basal basalts and overlying Peach Springs Tuff imply major eruptive phase between 17 and 19 my ago.

24. Location of lowest basalt (resting on granite) dated from base of Aquarius Mountain section. Section exposed in stream south of Austin Peak. (Age 18.2± 1.5 my.) Underlies Peach Springs Tuff (Young and McKee, 1978, in press).

25. Prevolcanic gravels in contact with granite at base of Snow Mountain (26) section. 600 to 700 feet of gravel composed of Precambrian clasts dips 10°-18° to NNE. Imbrication indicates stream flow to NE.

26. Snow Mt. Mesa-forming volcanic units containing abundant quartz crystals showing resorption or reaction rims. Source of flows was to the west and extensive erosion occurred before Aquarius Mts. eruptions. Dates of 24.7± 3.5 and 24.9± 0.9 my have been obtained from basalts near the base of a similar section about 3 miles south of Snow Mountain (Young and McKee, 1978, in press). Section rests on thick prevolcanic gravels at Snow Mt., but underlying gravels observed elsewhere are only a few inches to a few feet thick.

27. Continuation of Tertiary channel from Milkweed Canyon into Hindu and Lost Man Canyons, connecting to Hurricane fault valley in Peach Springs Canyon.

28. Kingman

29. Colorado River

30. Well to bedrock from elevation of 3331 feet. Peach Springs Tuff occurs at 650 to 760 foot depth and bedrock is at 910 feet.

31. Well with surface elevation of 3300 feet penetrated volcanic section at 890 to 1040 feet (bottom of hole).

32. Well with surface elevation of 3130 shows neither bedrock nor volcanic rocks to depth of 929 feet.

33. Well with surface elevation of 3340 feet shows neither bedrock nor volcanics to depth of 1247 feet.

34. Well with surface elevation of 3470 feet contains volcanic section from 750 to 825 foot depth in section 880 feet thick (no bedrock).

35. Well with surface elevation of 3704 feet contains volcanic section from 159 to 590 foot depth and probable bedrock (granite) at 590 feet.

36. Hualapai Mts. (8266 elev.)

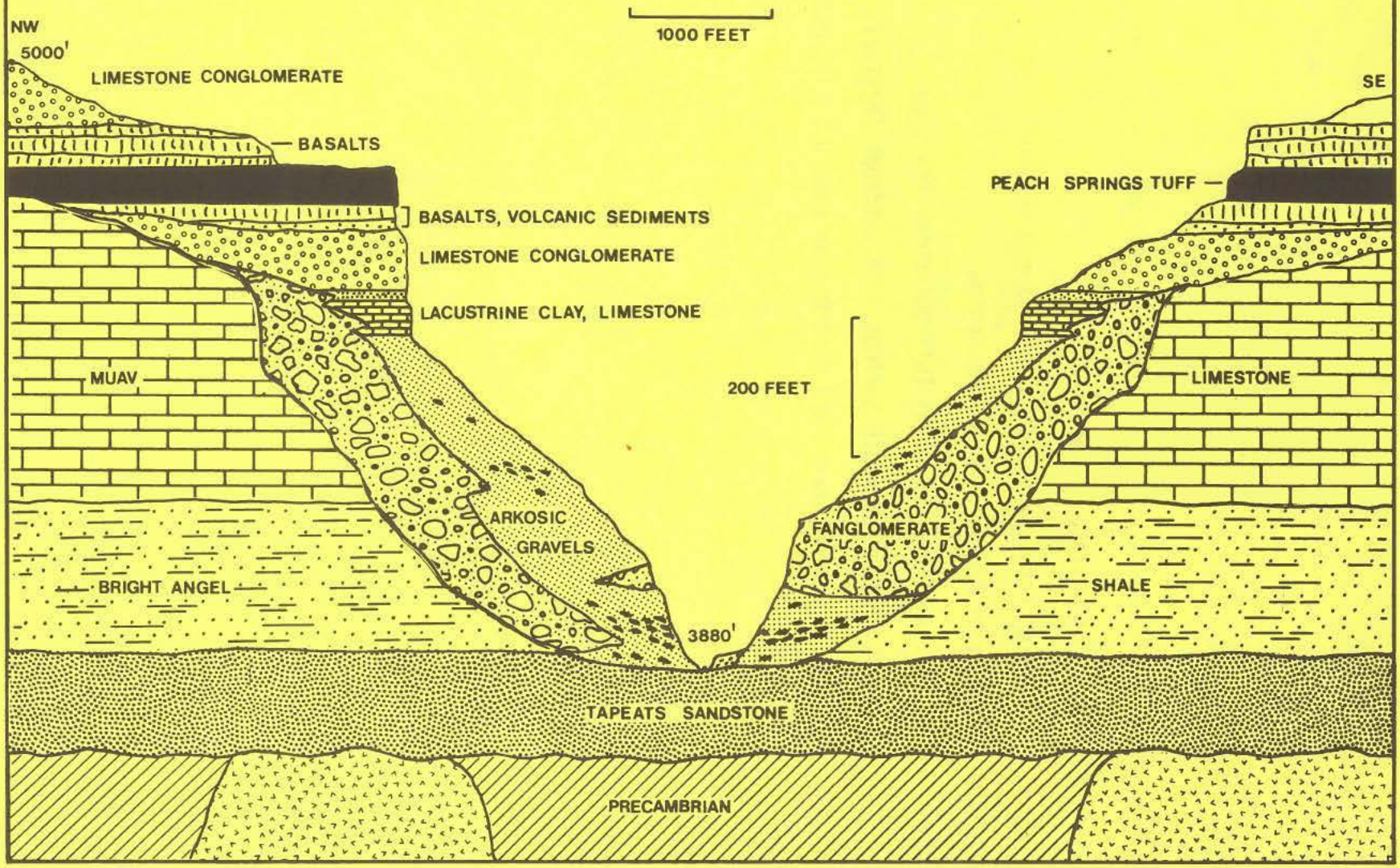
37. Truxton (also center of prevolcanic valley eroded along Hurricane fault zone to depth of 600+ feet below present surface).

38. Meriwhitica Monocline

Figures

FIG. 1

MILKWEED CANYON
DIAGRAMMATIC CROSS SECTION



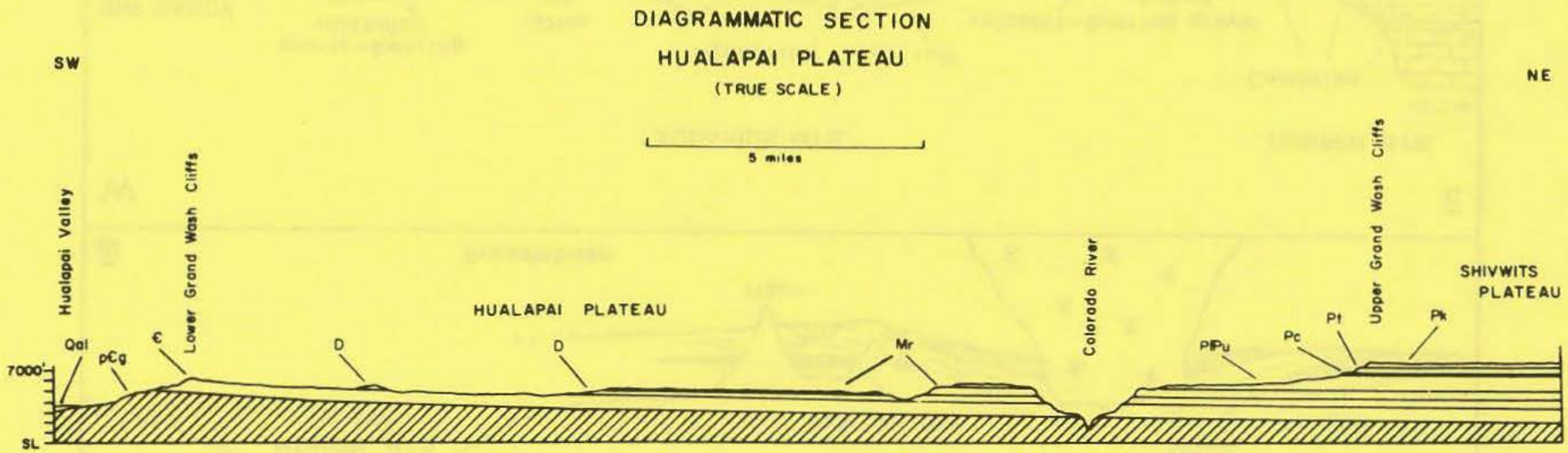

DIAGRAMMATIC SECTION
HUALAPAI PLATEAU
(TRUE SCALE)
5 miles
SW
NE
Hualapai Valley
Lower Grand Wash Cliffs
HUALAPAI PLATEAU
Colorado River
Upper Grand Wash Cliffs
SHIVWITS PLATEAU
Qal
pCg
€
D
D
Mr
PIPu
Pc
Pt
Pk
7000'
SL

FIG. 2

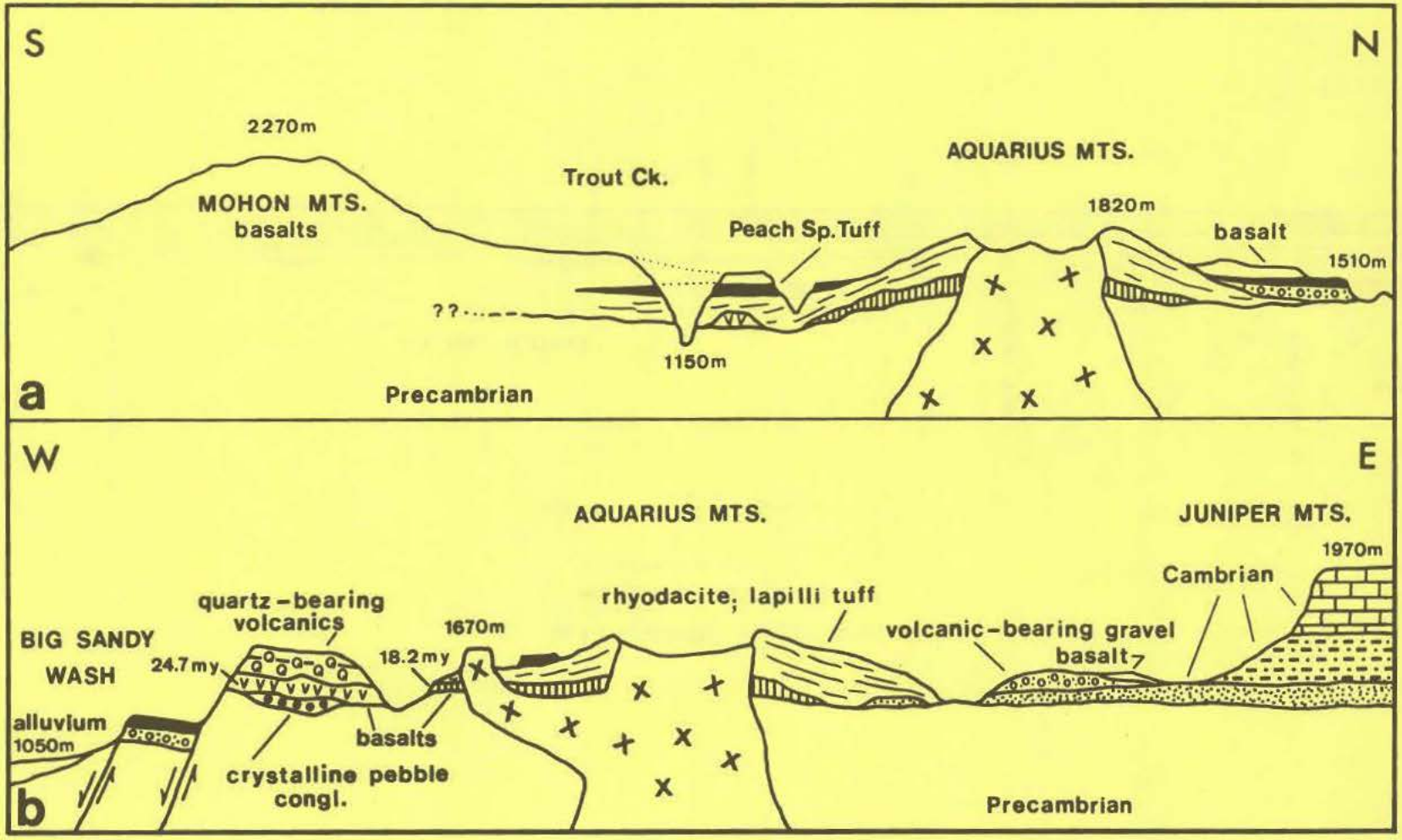

S
N
2270m
MOHON MTS.
basalts
Trout Ck.
AQUARIUS MTS.
1820m
Peach Sp.Tuff
basalt
1510m
??
1150m
a
Precambrian
W
E
AQUARIUS MTS.
JUNIPER MTS.
1970m
Cambrian
quartz-bearing
volcanics
rhyodacite, lapilli tuff
1670m
volcanic-bearing gravel
basalt
BIG SANDY
WASH
24.7my
18.2my
alluvium
1050m
basalts
crystalline pebble
congl.
b
Precambrian

FIG. 3

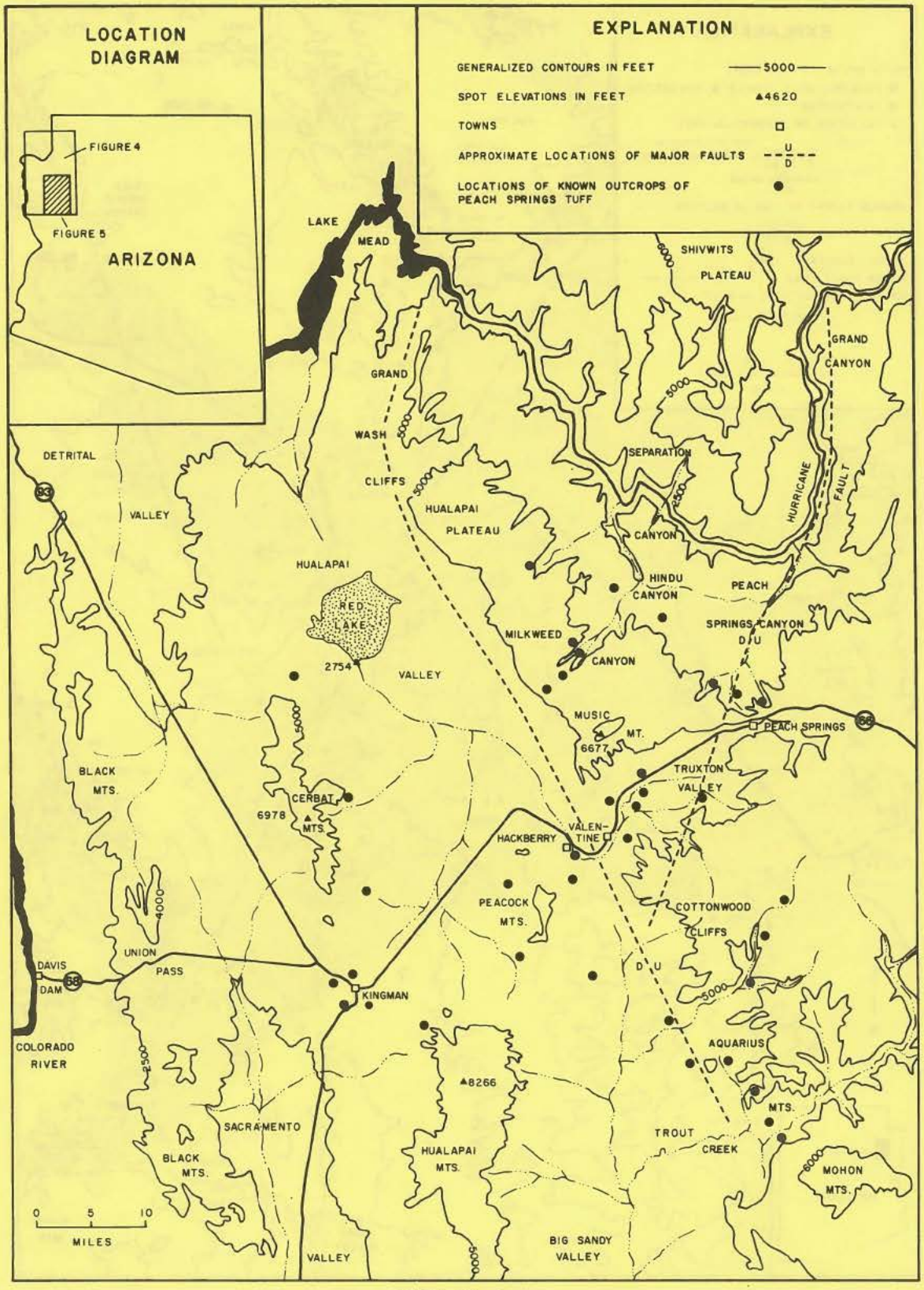

LOCATION DIAGRAM
FIGURE 4
FIGURE 5
ARIZONA
EXPLANATION
GENERALIZED CONTOURS IN FEET
5000
SPOT ELEVATIONS IN FEET
4620
TOWNS
APPROXIMATE LOCATIONS OF MAJOR FAULTS
U
D
LOCATIONS OF KNOWN OUTCROPS OF PEACH SPRINGS TUFF
LAKE MEAD
SHIVWITS PLATEAU
GRAND CANYON
GRAND WASH CLIFFS
DETRITAL VALLEY
HUALAPAI PLATEAU
SEPARATION CANYON
HURRICANE FAULT
HINDU CANYON
PEACH SPRINGS CANYON
HUALAPAI VALLEY
RED LAKE
2754
MILKWEED CANYON
MUSIC MT.
6677
PEACH SPRINGS
TRUXTON VALLEY
BLACK MTS.
CERBAT MTS.
6978
HACKBERRY
VALENTINE
PEACOCK MTS.
COTTONWOOD CLIFFS
UNION PASS
DAVIS DAM
KINGMAN
COLORADO RIVER
AQUARIUS MTS.
8266
SACRAMENTO BLACK MTS.
HUALAPAI MTS.
TROUT CREEK
MOHON MTS.
0 5 10
MILES
VALLEY
BIG SANDY VALLEY

FIGURE 4

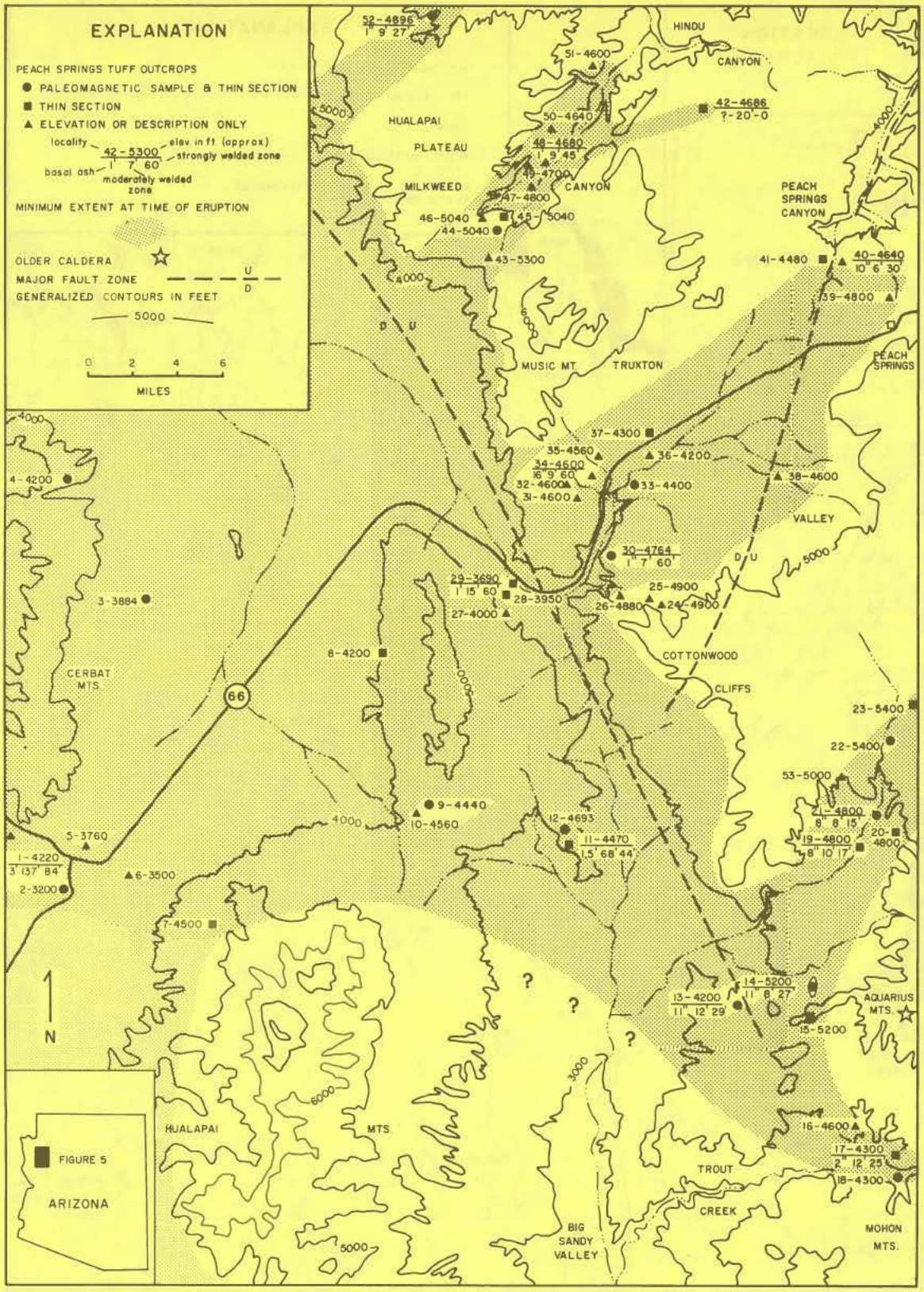

EXPLANATION
PEACH SPRINGS TUFF OUTCROPS
PALEOMAGNETIC SAMPLE & THIN SECTION
THIN SECTION
ELEVATION OR DESCRIPTION ONLY
locality
elev. in ft. (approx)
strongly welded zone
basal ash
moderately welded zone
MINIMUM EXTENT AT TIME OF ERUPTION
OLDER CALDERA
MAJOR FAULT ZONE
GENERALIZED CONTOURS IN FEET
5000
0 2 4 6
MILES
HINDU
CANYON
HUALAPAI
PLATEAU
MILKWEED
CANYON
PEACH
SPRINGS
CANYON
MUSIC MT.
TRUXTON
PEACH
SPRINGS
VALLEY
COTTONWOOD
CLIFFS
CERBAT
MTS.
66
AQUARIUS
MTS.
HUALAPAI
MTS.
TROUT
CREEK
BIG
SANDY
VALLEY
MOHON
MTS.
N
FIGURE 5
ARIZONA

FIGURE 5

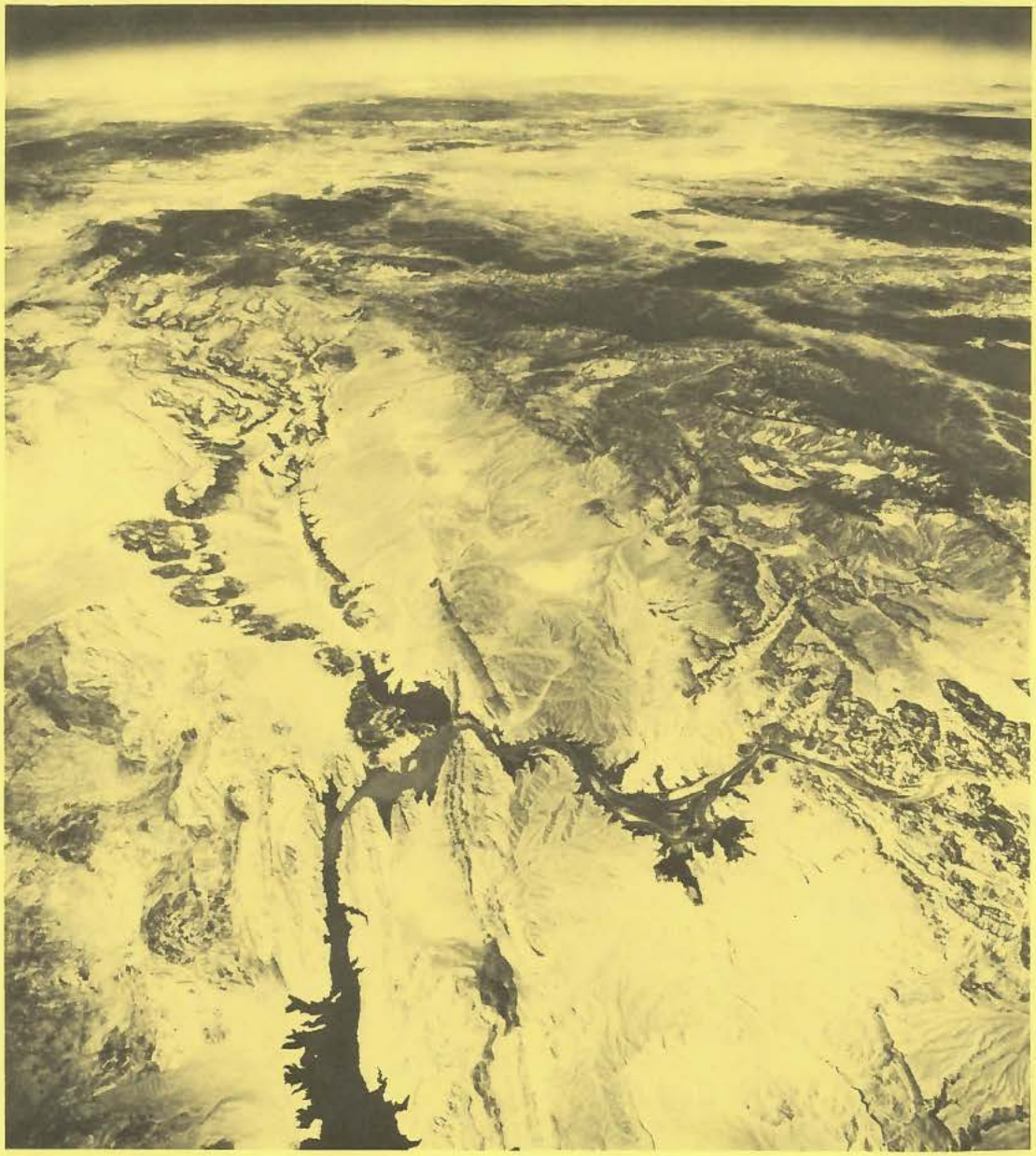


FIGURE 6

SUBJECT INDEX*

*Pagination refers to first page of paper in which subject is cited.

AUTHOR INDEX*

*Pagination refers to first page of paper in which author is cited.

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NOTES

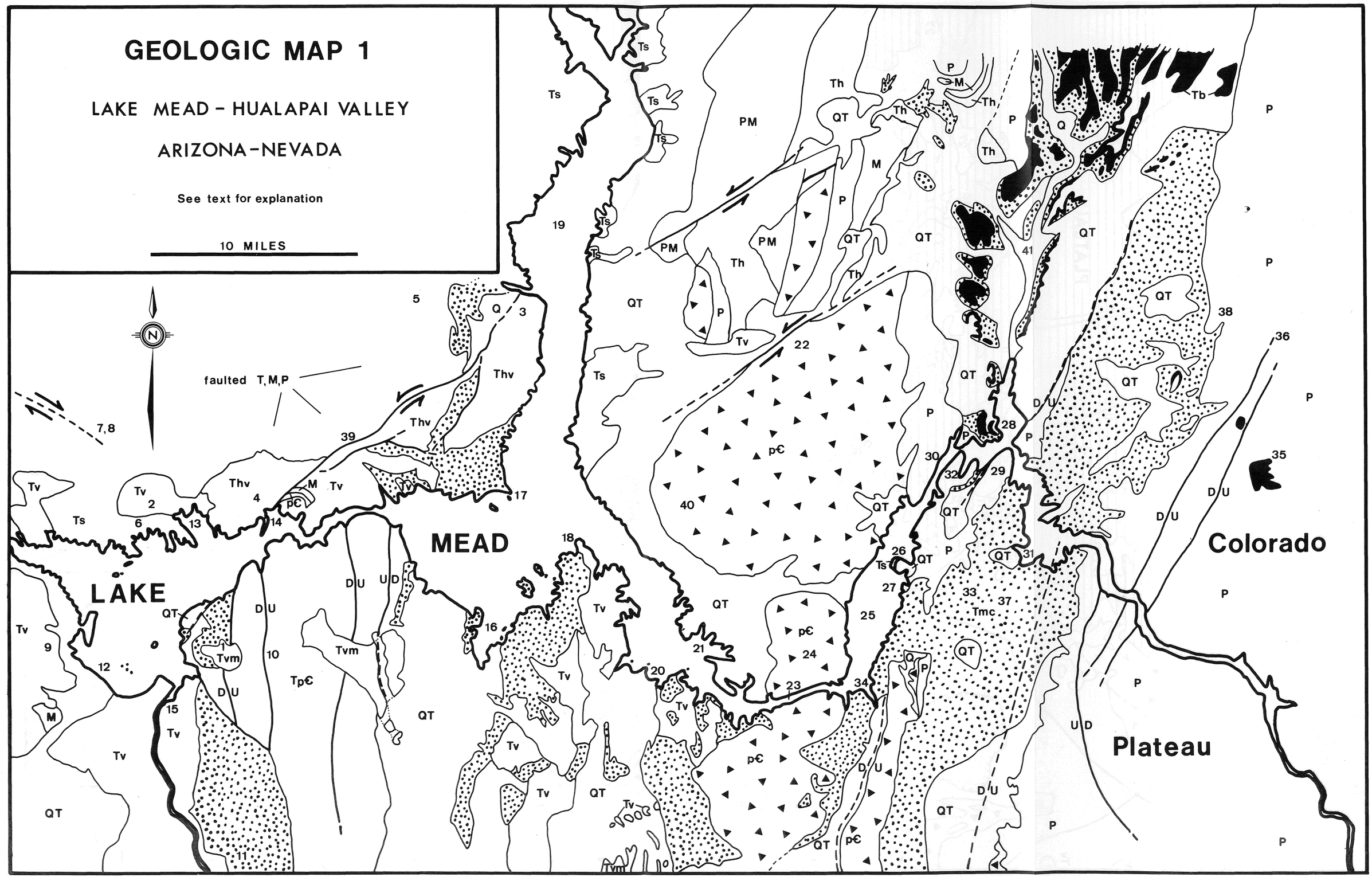
GEOLOGIC MAP 1

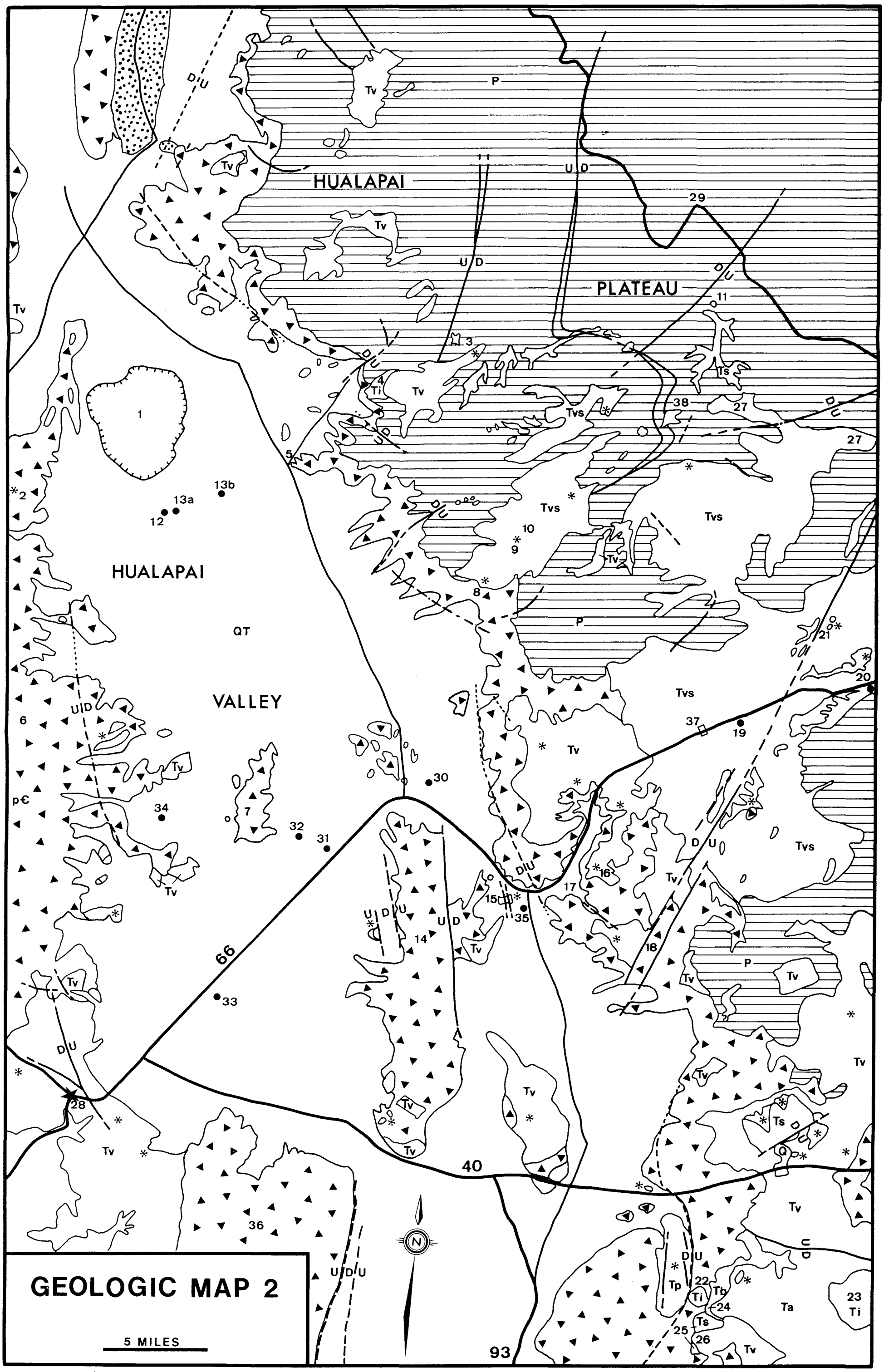
LAKE MEAD - HUALAPAI VALLEY

ARIZONA-NEVADA

See text for explanation

10 MILES





GEOLOGIC MAP 2

NASA
National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas 77058