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TRIASSIC AND JURASSIC GEOLOGY OF THE SOUTHERN COLORADO PLATEAU

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ABSTRACT

Triassic and Jurassic rocks on the southern Colorado Plateau comprise an important section of chiefly continental and minor marine deposits. Triassic rocks are naturally subdivided by a major regionwide unconformity into the Lower and Middle Triassic Moenkopi Formation and Upper Triassic Chinle Formation. The Moenkopi Formation consists of fine-grained redbeds and minor carbonate of fluvial, tidal-flat, and shallow-marine origin; continental environments dominated the eastern part of the region and mixed environments the western part. The Chinle Formation was everywhere formed by continental processes; coarse-grained siliciclastics and carbonate formed in floodplain and lucustrine environments.

Lower and Middle Jurassic rocks are primarily cross-stratified sandstone, redbeds, and minor carbonate. They are subdivided into related units by regionwide unconformities. The oldest Jurassic rocks consist of the eolian Wingate Sandstone, flanked to the southwest by fluvial deposits of the Moenave Formation. The Kayenta Formation forms a widespread fluvial succession that grades upward into the eolian Navajo Sandstone. Distribution of the overlying eolian- and sabkha-formed Temple Cap Sandstone is restricted to the Zion National Park area by unconformities. Bounded by unconformities is the widespread sequence consisting of the Page Sandstone (eolian), Carmel Formation (marine to continental), and Entrada Sandstone (eolian). The Entrada Sandstone grades eastward into lacustrine-formed rocks of the Wanakah Formation. Restricted by unconformities to primarily the Henry Mountains-Kaiparowits region and areas to the north are the Curtis and Summerville Formations. The Curtis Formation is a marine sandstone and mudstone, and the Summerville Formation comprises fine-grained sandstone and mudstone of restricted-marine origin. The southern and eastern margins contain eolian deposits, the Romana Sandstone and Moab Tongue of the Entrada Sandstone, respectively.

Upper Jurassic rocks of the Morrison Formation unconformably overlie older Jurassic rocks. The Morrison comprises a heterogeneous suite of rocks, mostly siliciclastics, and is divided into several members. The Tidwell Member formed on arid floodplains and in saline lakes and grades into eolian deposits of the Bluff Sandstone Member and coeval Junction Creek Sandstone. The Salt Wash Member is of fluvial-lacustrine origin, and the Recapture Member includes deposits of fluvial, eolian, and sabkha origin. The Westwater Canyon Member is chiefly of fluvial origin and the Brushy Basin Member was deposited in fluvial and lacustrine settings.

Triassic and Jurassic rocks on the Colorado Plateau not only reflect the depositional and tectonic history of the Colorado Plateau region, they also yield clues about growing tectonic unrest to the west and south of the region. The sediment record of the Nevadan and early Sevier orogenies is reflected in these rocks.

INTRODUCTION

Area and Stratigraphic Interval

Triassic and Jurassic sedimentary rocks are extensively exposed across much of the southern Colorado Plateau and form one of the finest ancient examples of chiefly continental deposits in the world. The area of study is centered on northern Arizona and southern Utah but also includes adjacent areas to provide a regional stratigraphic framework. Triassic rocks generally crop out in narrow belts flanking major uplifts and also occur in a broad outcrop belt in the Little Colorado River valley; Jurassic rocks form moderately broad outcrop belts between the various uplifts (fig. 1). Cretaceous strata crop out in several large basins throughout the region.

Three intermixed lithologic assemblages form much of the Triassic and Jurassic rock sequences: (1) redbeds consisting of mudstone and thin sandstone deposited in paralic, coastal-plain, and fluvial-lacustrine environments; (2) lenticular and amalgamated lenticular sandstone and conglomerate deposited in fluvial channels; and (3) large-scale, cross-stratified, sheetlike quartz arenites deposited in eolian environments. Less abundant are limestone and dolomite, which formed in shallow-marine, coastal-plain, and lacustrine environments, and gypsum, which formed on coastal plains.

Methods, Philosophy, and Purpose

Data and interpretation have been gathered from recent studies including numerous unpublished master's theses. Review of and reference to older work is made only when not superseded by newer studies. The level of confidence of the interpretations in this paper is indicated, and areas in need of additional study are identified. The strata are divided into superimposed divisions, most of which are

TABLE 1. Stratigraphic names used in this report and abbreviations used on many figures.

Jm—Morrison Formation
- Jmb—Brushy Basin Member
- Jmw—Westwater Canyon Member
- Jmr—Recapture Member
- Jms—Salt Wash Member
- Jmbl—Bluff Sandstone Member
- Jmt—Tidwell Member

Jj—Junction Creek Sandstone
Js—Summerville Formation

Jr—Romana Sandstone

Jwk—Wanakah Formation

Jz—Zuni Sandstone

Jcr—Curtis Formation
Jtd—Todilto Formation
Je—Entrada Sandstone
- Jec—Cow Springs Member
- Jem—Moab Tongue
- Jes—Slick Rock Member
- Jed—Dewey Bridge Member
- Jei—Iyanbito Member

Jc—Carmel Formation
- Jcu—Upper Member
- Jcw—Winsor Member
- Jcp—Paria River Member
- Jcc—Crystal Creek Member
- Jcj—Judd Hollow Member (Tongue)

Jp—Page Sandstone
- Jpt—Thousand Pockets Tongue
- Jph—Harris Wash Tongue

Jt—Temple Cap Sandstone
- Jtw—White Throne Member
- Jts—Sinawava Member

Jn—Navajo Sandstone
- Jnl—Lamb Point Tongue
- Jns—Shurtz Sandstone Tongue

Ja—Aztec Sandstone

Jk—Kayenta Formation
- Jkt—Tenney Canyon Tongue
- Jkc—Cedar City Tongue

Jmv—Moenave Formation
- Jmvs—Springdale Sandstone Member
- Jmvw—Whitmore Point Member
- Jmvd—Dinosaur Canyon Member

Jw—Wingate Sandstone

TRc—Chinle Formation
- TRcc—Church Rock Member (includes some strata previously assigned to the Rock Point Member, Wingate SS)
- TRco—Owl Rock Member
- TRcp—Petrified Forest Member
- TRck—Kane Springs strata
- TRcm—Moss Back Member
- TRcb—Monitor Butte Member
- TRcs—Shinarump Member
- TRct—Temple Mountain Member

TRd—Dolores Formation
TRm—Moenkopi Formation
- TRmh—Holbrook Member
- TRmk—Moqui Member
- TRmw—Wupatki Member
- TRmu—Upper Red Member
- TRmsh—Shnabkaib Member
- TRmm—Middle Red Member
- TRmv—Virgin Limestone Member
- TRml—Lower Red Member
- TRmt—Timpoweap Member
- TRmmc—Moody Canyon Member
- TRmto—Torrey Member
- TRms—Sinbad Limestone Member
- TRmb—Black Dragon Member
- TRmho—Hoskinnini Member

FACIES ANALYSIS

Triassic and Jurassic rocks (table 1) are divided into 17 lithofacies shown on table 2. Each is assigned a three-letter acronym. Some facies yield rather clear interpretations of depositional processes and environments; others yield less certain interpretations in which cases environmental analysis is best determined by stratigraphic relations. Regional lithologic data are presented in figure 9.

TRIASSIC STRATIGRAPHY

Moenkopi Formation

Facies. The Moenkopi Formation consists of a westward-thickening wedge of fine-grained red clastics in the east and progressively increasing amounts of carbonate to the west (fig. 3). Regional description and interpretation are by Bissell (1969), Irwin (1971), Stewart and others (1972a), Baldwin (1973), Blakey (1974), and Nielson and Johnson (1979). The following brief discussion together with table 2 and figures 3, 6, and 9 outlines Moenkopi depositional trends, which are:

1. On the Colorado Plateau, red fine-grained clastics, facies SSM and RMS (table 2), dominate the Moenkopi.
2. Medium- and coarse-grained clastics (HCS, LCS) form lobate (Blakey, 1974) and elongate (Stewart and others, 1972a) incursions in southeastern Utah and the Little Colorado valley, respectively.
3. Thickness and lithology vary abruptly in the Salt Anticline region due to syndepositional salt-controlled tectonics (Stewart and others, 1972a).
4. Two thin carbonate packages extend southeastward into the redbed package; the lower is the Sinbad-Timpoweap and the upper is the Virgin.
5. Gypsum and gypsiferous mudstone form an important component in the upper third in many areas.
6. West of the Colorado Plateau and the Wasatch line the percentage of carbonate increases abruptly; near Las Vegas, Nevada, over 50 percent of the formation is limestone (Bissell, 1969).

Interpretation. Interpretation of the above trends clearly indicates that much of the Moenkopi formed on a very gently dipping coastal plain. There is some disagreement as to percentages of nonmarine coastal-plain versus

TABLE 2. Facies description and interpretation showing abbreviations of units containing these facies

FACIES	DESCRIPTION	INTERPRETATION	DISTRIBUTION Dominant	Common	Present to Rare
large-scale cross-stratified sandstone (CSS)	Mature to supermature very fine to medium-grained quartz arenite. Dominant sedimentary structure is large-scale, angle-of-repose planar-tubular to planar-wedge, or trough cross-stratification. Sets vary from simple to compound (intraset) and are up to 30 m thick. Facies geometry dominantly broad, regionally extensive sheets but includes smaller lenses, pods, and wedges.	Formed by migrating eolian dunes and draas. Most are associated with major erg deposits though some represent small dune fields. Examples and detailed criteria provided by Hunter (1981), Kocurek (1981), Blakey and others (1983), Middleton and Blakey (1983), Rubin and Hunter (1983), Hunter and Rubin (1983). Possibly marine deposits discussed by Blakey and others (1983).	Jw, Jn, Jtw, Jp, Je, Jmbl, Ja	Jmvd, Jmr Possibly marine: Jpt, Jcc	Jcu
horizontally laminated to cross-stratified sandstone (HCS)	Submature to supermature, very fine to medium-grained quartz to subfeldspathic arenite. Dominant sedimentary structure is horizontal lamination, low-angle cross-stratification, but facies may include small- to medium-scale cross-stratification, ripple lamination and ripple marks, and plane-bed lamination. Sets are simple or compound and generally range from 0.5 - 6.0 m thick. Broad, thin sheets are dominant geometry.	A. Formed in variety of shoreline to nearshore shallow-marine environments. Deposits resemble modern beach and tidal-generated sand bodies but stratigraphic position and association with marine fossiliferous units are best criteria (Blakey, 1974; Abendshein, 1978; Smith and others, 1963).	Jcr	TRmw, TRmb	Jcu
		B. Eolian erg-margin deposits. Sand from adjacent erg blown into and modified by various environments and processes (Hunter, 1981; Kocurek, 1981; Middleton and Blakey, 1983).		Jw, Jn, Jp, Je, Jr, Jmbl	Jcu
wavy-bedded to ripple-laminated sandstone (WBR)	Submature to mature quartz and subfeldspathic arenite; very fine to medium grained, may be silty. Heterogeneous assemblage of mostly small-scale structures including irregular wavy lamination, wave-ripple lamination, climbing translatent strata, crinkly bedding, plane-bed lamination, and small-scale cross-stratification. Beds typically tabular and extensive, but may be intimately interbedded with other facies.	Erg-margin interdune and eolian sand-sheet deposits. Variety of wet and dry environments including sabkha, lacustrine, and wadi deposits in which chief source of sand is adjacent dunes (Kocurek, 1981; Blakey and Middleton, 1984).	TRmho	TRd, TRcc, Jmvd, Jn, Je, Jw, Jk, Jp	Jc
lenticular cross-stratified sandstone (LCS)	Immature to mature sandstone of varying composition and grain size; may be pebbly. Diagnostic character is lensoid (channel) shape of individual beds, which singularly or in multiples form ribbon, narrow-sheet, or broad-sheet sandstone bodies (terminology of Blakey and Gubitosa, 1984). Internally, the bodies contain combinations of horizontal plane-bed, trough, planar-tabular, or epsilon cross-stratification. Bases of beds are sharp and scoured and may or may not fine upward. Individual beds typically range from 1-5 m thick; amalgamated sheet-sandstone bodies may be nearly 100 m thick.	Deposited as fluvial-channel and (or) point-bar deposits. Examples and detailed criteria provided by Dubiel (1983), Blakey and Gubitosa (1984), Peterson (1984). Distribution to right shows chiefly braided-stream deposits above line and meandering stream deposits below.	TRcs, TRcm, Jmvs, Jk, Jms	TRcb, Jmr, Jmw, TRck, TRd	Jcu
			TRmh, TRcp Jms	TRcb, TRck, Jmr, Jmvd, Jmb, Jk	

TABLE 2. Facies description and interpretation showing abbreviations of units containing these facies (continued)

FACIES	DESCRIPTION	INTERPRETATION	DISTRIBUTION		
			Dominant	Common	Present to Rare
silty sandstone (STS)	Very fine grained silty sandstone; grain size typically bridges sand-silt boundary. Sedimentary structures include wispy lamination, ripple lamination, plane-bed lamination, small-scale cross-stratification, and structureless or homogeneous bedding. Body geometry ranges from regionally continuous broad sheets to small pods or lenses. Either or both upper and lower contacts can be sharp or gradational typically with finer grained facies.	Chiefly product of shallow, unconfined aqueous flows, although some units modified by pedogenic processes. Specific environments, generally diagnosed by stratigraphic position, include flood-plain and pedogenic (Blodgett, 1984; Sargent, 1984; Edwards, 1985), erg-margin and flashy braided-stream or wadi (Edwards, 1985), and sabkha to high intertidal (Blakey, 1974) deposits.	TRmho	TRmu, TRd, TRcc, Jmvd, Jk, Jwk, Je	
sandstone and mudstone (SSM)	Interbedded sandstone, chiefly HCS, WBR, STS, and mudstone, RMS. Typically forms significant heterogeneous redbed assemblages tens to over 100 m thick with individual beds generally less than 1 m thick. Wide range of sedimentary structures includes ripple marks, mud cracks, salt-crystal casts, flaser bedding, mud-pebble rip-up clasts, small-scale cut and fill, sole marks, tool marks, and small-scale cross-stratification.	Product of alternating traction and suspension deposition, unconfined current flow, both lower and upper flow regime, desiccation, and sabkha processes. Specific environment of deposition determined by stratigraphic position and includes flood basin and lacustrine (Klockenbrink, 1979; Peterson, 1984; Edwards, 1985), tidal flat (Blakey, 1974; Geesaman, 1979), and possibly subtidal (Blakey, 1974; Caputo, 1980).		TRm, TRd, Jk, Je, Js, TRc, Jmvd, Jc, Jwk, Jm	
red mudstone to siltstone (RMS)	Red mudstone to siltstone, structureless to ripple laminated, some units very micaceous. Sedimentary structures similar to those of SSM. Differentiated from SSM by subordinate or rare, rather than subequal, amounts of sandstone.	Suspension and low-energy traction deposits formed in flood basin (Stewart and others, 1972a,b), lacustrine (Gubitosa, 1981), tidal-flat, and subtidal (Blakey, 1974) environments.	TRm	TRc, TRd, Jmvd, Jmvw, Jk, Jts, Jc, Jwk, Js, Jmt, Jmr	Je
bentonitic mudstone (BMS)	Mudstone, varigated, bentonitic, generally poorly exposed due to swelling nature of clays. Abundant in Chinle and Morrison Formations and a subordinate lithology in several other units.	Chiefly suspension deposits in flood-basin and lacustrine environments (Stewart and others, 1972b; Blakey and Gubitosa, 1983), but may also form in coastal-plain and tidal environments (Caputo, 1980).	TRcp, Jmb	TRcb, TRck, Jk, Jcu, Jts	
calcareous mudstone (CMS)	Calcareous mudstone, pale reddish-brown to tannish-gray. Sedimentary structures similar to those of SSM. Generally accessory facies associated with other fine-grained and carbonate facies. May be poorly exposed.	Suspension and low-energy traction deposits associated with subtidal (Voorhees, 1978; Geesaman, 1979), coastal-plain (Blakey and others, 1983), and lacustrine (Gubitosa, 1981; Klockenbrink, 1979) depositional systems.		TRck, Jmvw, Jcj, Jtd, Jmt, Jcp, Jcr	TRm
black mudstone (BLM)	Black fetid to sulfurous mudstone; forms part of lower Monitor Butte Member of Chinle Formation along western Monument Upwarp.	Lacustrine to paludal, anoxic bottom conditions (Blakey and Gubitosa, 1983; Dubiel, 1983).		TRcb	

TABLE 2. Facies description and interpretation showing abbreviations of units containing these facies (continued)

FACIES	DESCRIPTION	INTERPRETATION	DISTRIBUTION: Dominant	DISTRIBUTION: Common	DISTRIBUTION: Present to Rare
aphanitic dolomite to limestone (DOL or ALS)	Aphanitic carbonate rock ranging from limestone to dolomite. Textures include micritic and microsparitic; sedimentary structures include algal laminations and rare ripple laminations. Forms thin sheets or sheets or localized pods; may be cherty.	Low-energy carbonate environments including restricted-marine shelf (Voorhees, 1978; Blakey, 1974), coastal-plain sabkha (Geesaman, 1979), lacustrine (Gubitosa, 1981).		TRmt, TRms, TRmv, TRmsh, TRc, Jcp, Jcj, Jtd	Jw, Jmv, Jk, Jn, Ja
silty limestone to dolomite (SLS or SDO)	Silty limestone to dolomite, chiefly micritic; gradational with but differentiated from DOL and ALS by terrigenous silt content which may amount to 50% of rock.	Similar to DOL and ALS; some units in Chinle and Dolores Formations of pedogenic origin (Gubitosa, 1981; Blodgett, 1984).		TRmt, TRms, TRmv, TRmsh, TRck, TRco, Jcj, Jcp	
peloidal limestone (PLS)	Peloidal limestone, chiefly peloidal packstone and wackestone, typically flaggy bedded. Peloids include pellets, micritized oolites, and small intraclasts. Most units sparsely fossiliferous (chiefly molluscan fauna). Forms local to subregional sheets.	Moderate-to low-energy marine shelf (Auld, 1976; Blakey and others, 1983).		TRmt, TRms, TRmv, Jcj, Jcp	
skeletal to oolitic limestone (SOL)	Skeletal to oolitic limestone, chiefly skeletal to oolitic packstone and grainstone. Flaggy to massive bedded, locally cross-stratified. Dominant molluscan fauna also includes forams, brachiopods, bryozoans, and conodonts. Units form local to subregional sheets.	Open-marine shelf with submarine bars and shoals (Blakey, 1974, 1979; Voorhees, 1978).		TRmt, TRms, TRmv, Jcj	
bedded gypsum (GYP)	Chicken-wire to recrystallized gypsum with varying percentages of silt and sand. Forms thin seams, lenses, and thick extensive sheets.	Evaporite deposits formed in lacustrine (Klockenbrink, 1979), sabkha, and highly restricted marine (Voorhees, 1978; Blakey, 1974) environments.		TRmm, TRmsh, TRmb, TRmmc, Jcp, Jmt, Jtd	TRml, TRmho
siliceous-pebble conglomerate (SCG)	Conglomerate composed of extrabasinal siliceous pebbles, chiefly quartz, quartzite, and chert, but also granitic and volcanic rock fragments. Associated with and containing bedding and sedimentary structures similar to those of facies LCS.	Coarse-grained fluvial deposits; see facies LCS.		TRd, TRcs, TRcb, TRcm, TRcp, TRck, TRcc, Jms, Jmb	TRmt, TRmb, TRmho
intraformational conglomerate (ICG)	Conglomerate composed of intrabasinal pebbles such as carbonate intraclasts, siltstone and mudstone pebbles, and rarely sandstone rip-up clasts. Otherwise similar to SCG.	Coarse- and fine-grained fluvial deposits. Clasts ripped from adjacent floodplain, lacustrine, and pedogenic environments (Gubitosa, 1981). Locally marine shoreline (Blakey, 1979).		TRmt, TRms, TRmto, TRmh, TRd, TRc, Jms	Jk

shallow-marine and tidal-flat deposits, but much of the Moenkopi formed within several meters of sea level (Stewart and others, 1972a; Baldwin, 1973; Blakey, 1974). Lobate sandstone in the Torrey Member of southeastern Utah has been interpreted as shallow-water deltaic deposits (Blakey, 1974; Abendshein, 1978). Linear sandstone and conglomerate in the Holbrook Member of the Little Colorado valley represent meandering stream deposits. Shallow-marine and tidal-flat deposits prevail in the Moenkopi west of the Colorado Plateau (Carr and Paull, 1983).

Chinle Formation

Facies. The Chinle Formation consists of heterogeneous clastic and minor carbonate rocks that formed in a broad basin with thickest preserved deposits south of the Four Corners along the Arizona-New Mexico state line (fig. 4). Several local and regional studies (Stewart and others, 1972b; Gubitosa, 1981; Blakey and Gubitosa, 1983, 1984; Pierson, 1984; Dubiel, 1983; Espegren, 1986) provide information for the following summary:

1. Bentonitic mudstone (BMS) is dominant across the southern area and red mudstone to siltstone (RMS) and

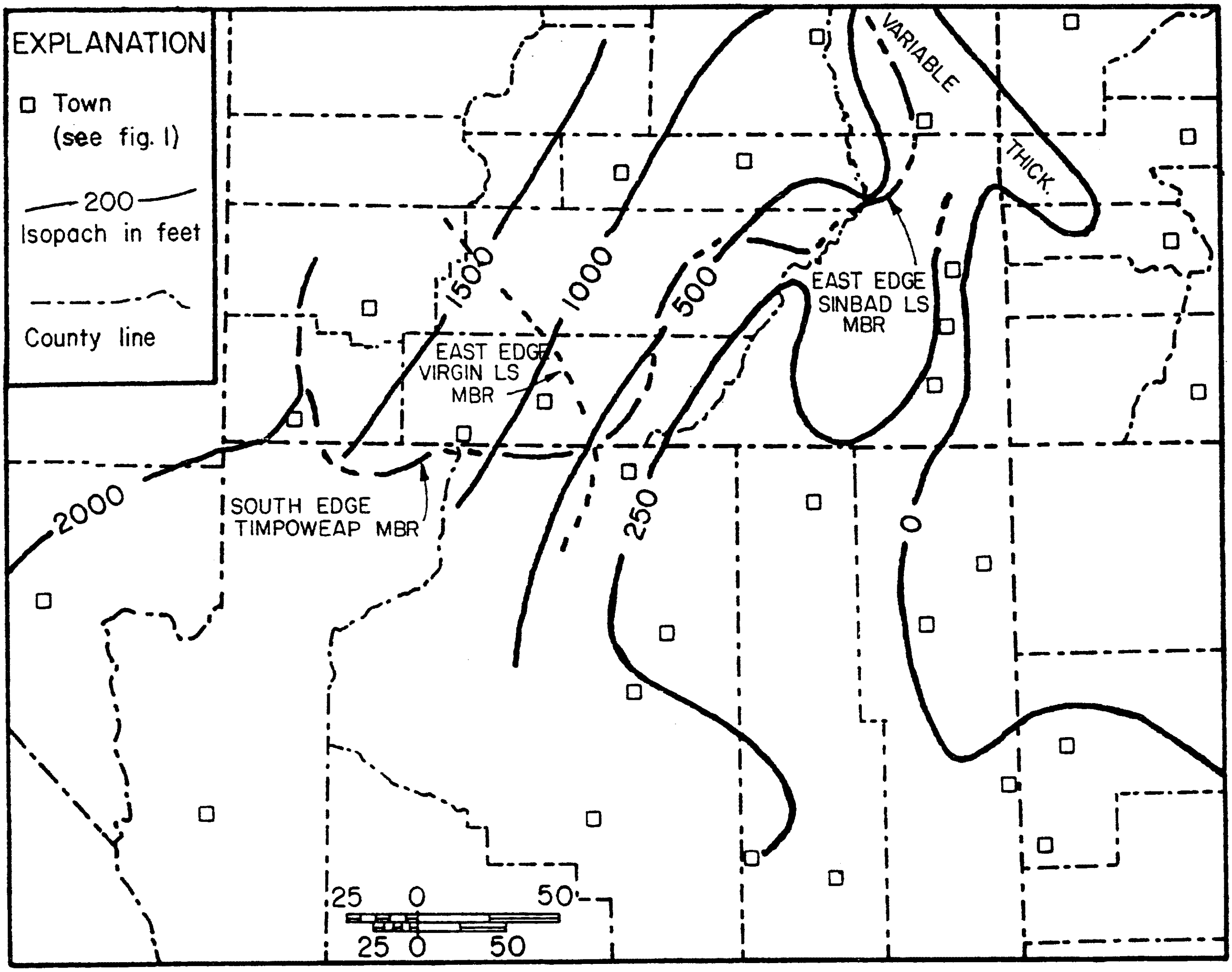


Figure 3. Isopach map of Moenkopi Formation showing southeast edge of three carbonate units (after Stewart and others, 1972a; Blakey, 1974). Thicknesses given in feet.

sandstone and mudstone (SSM) is dominant across the northern area of study (Stewart and others, 1972b).

2. Two broad sheets of lenticular cross-stratified sandstone (LCS; figs. 4, 6, and 9) form widespread deposits in the lower third of the formation (Stewart and others, 1972b; Blakey and Gubitosa, 1983).
3. Extensive aphanitic limestone (ALS) and silty limestone (SLS) are in the Owl Rock Member (Stewart and others, 1972b).
4. Intraformational conglomerate (ICG) and associated calcarenite (facies LCS) dominate the lower one-third of the formation in the Salt Anticline region (Gubitosa, 1981).
5. Westward thinning of the formation is a result of truncation by overlying Jurassic rocks (fig. 6).
6. Paleocurrent analysis indicates northwesterly flow of streams in the lower part of the formation followed by more irregular patterns in younger rocks (Stewart and others, 1972b).

The upper, chiefly nonbentonitic and noncalcareous portion of the Chinle Formation is in need of serious regional stratigraphic and sedimentologic study. In this paper I have followed the trend of using the term "Church Rock Member" for all of these strata; however, it appears that not all Church Rock as used herein and by many previous workers is correlative in either a time or lithologic sense. Further explanation of this problem is beyond the scope of this paper, and the reader is referred to discussions by O'Sullivan (1970), Stewart and others (1972b, p. 42), and Blakey and Gubitosa (1983, figs. 3, 10).

Interpretation. The Chinle Formation is entirely of continental origin (Stewart and others, 1972b). Braided-stream depositional systems formed the Shinarump and Moss Back Members and meandering-stream depositional systems and associated flood-basin and lacustrine environments dominate the Petrified Forest Member (Blakey and Gubitosa, 1983, 1984). Redbeds in the Church Rock Member formed by a variety of sheetflood,

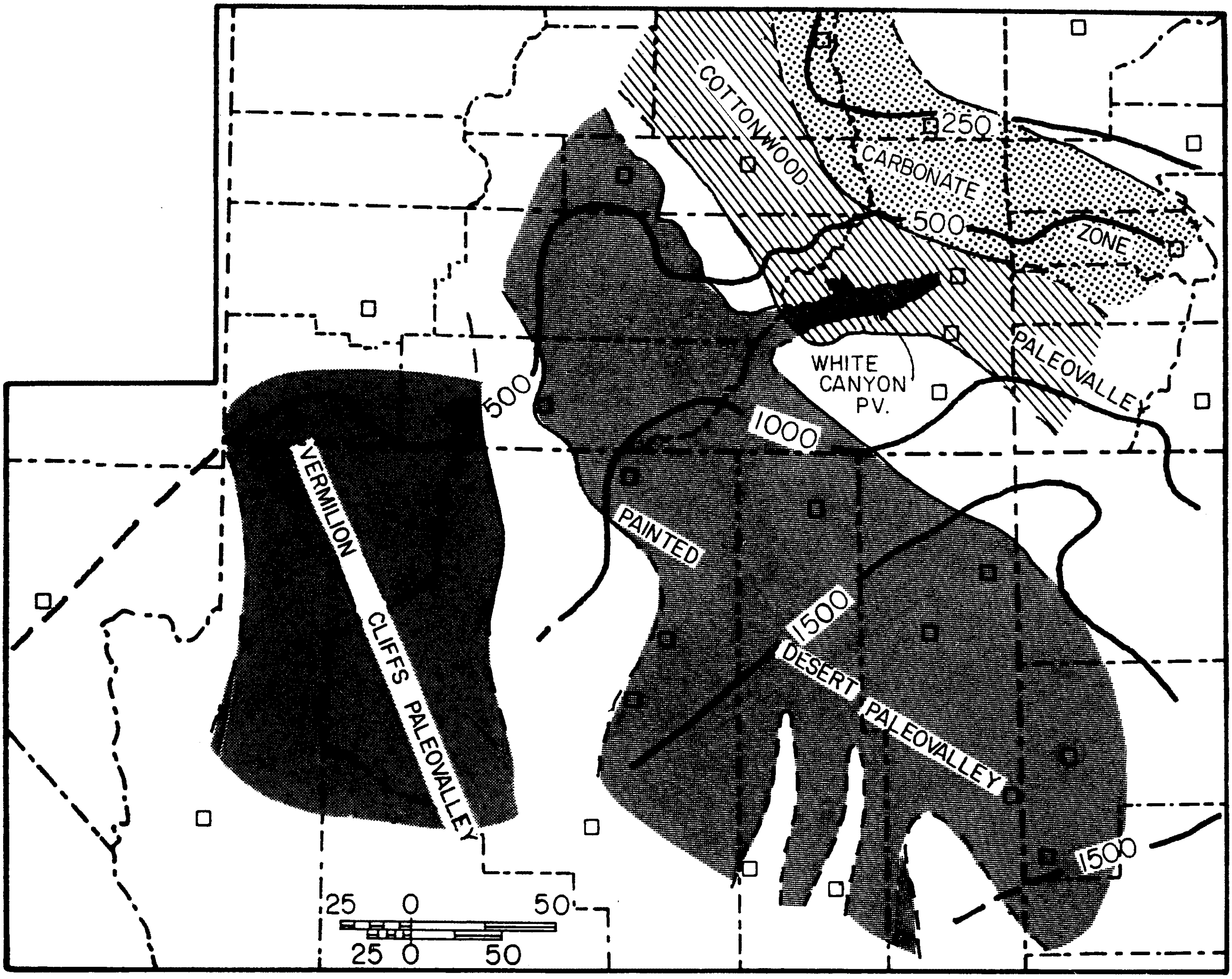
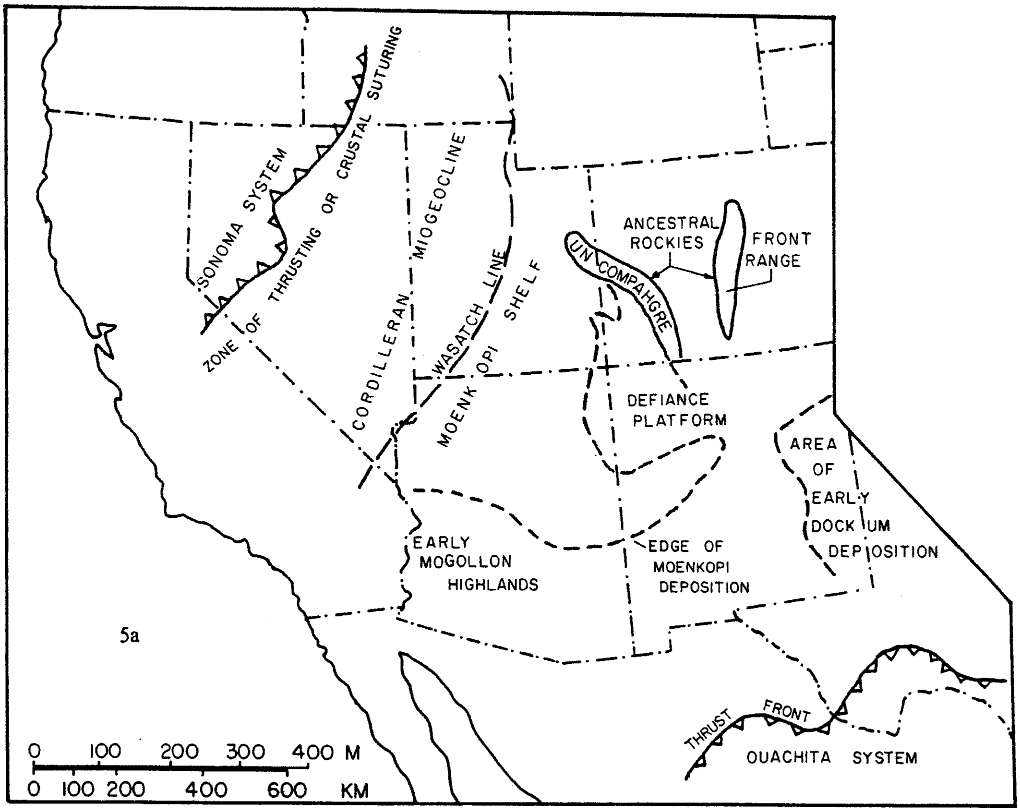


Figure 4. Isopach map of Chinle Formation (after Stewart and others, 1972b). Distribution of paleovalleys present during Shinarump and Moss Back Member deposition are also shown. Carbonate zone shows distribution of Kane Springs strata (Blakey and Gubitosa, 1983). Thicknesses given in feet.

lacustrine, pedogenic, and eolian processes (Stewart and others, 1972b; Blakey and Gubitosa, 1984), as did similar deposits in the Dolores Formation of southwestern Colorado (Blodgett, 1984).

Westward truncation of the Chinle may have been concurrent with deposition of the upper part of the formation in northeastern Arizona. Most paleocurrent data show that Shinarump, Monitor Butte, Moss Back, and most of the Petrified Forest streams flowed northwest to north (Stewart and others, 1972b) across the Colorado Plateau. However, latest Petrified Forest and Church Rock streams flowed in various directions and defined a crude internal drainage pattern that converged toward southeastern Utah (Poole, 1961; Stewart and others, 1972b). If the drainage did converge in southeastern Utah (note that this interpretation depends on a correct correlation of upper Chinle strata), there is a suggestion of gentle uplift to the south or southwest. Such uplift may have caused rivers to be deflected or flow toward the east. Furthermore, the magnitude of the unconformity between the Chinle and overlying Glen Canyon Group increases in a westerly direction (Pipiringos and O'Sullivan, 1978, p. A19, plate 1). For northeastern Arizona near the town of Chinle where the upper Chinle Formation is thickest, there is considerable difference of opinion as to the magnitude or even presence of an unconformity at the base of the Glen Canyon Group. In the Las Vegas area, presence of pebbles in the lowermost Glen Canyon Group (Marzolf, 1983) and in the Shinarump Member of the Chinle Formation suggests a southwestward or westward source.

Taken together, these independent lines of evidence suggest the presence of an uplift of uncertain magnitude along the southern and western margins of the Colorado Plateau during and immediately following Chinle deposition. Thus Chinle deposition and the unconformity at the base of the Glen Canyon Group suggest an early pulse of uplift off the south and west margins of the Colorado Plateau; such pulses became more frequent and eventually culminated in major orogeny during latest Jurassic time and continued through the Cretaceous.



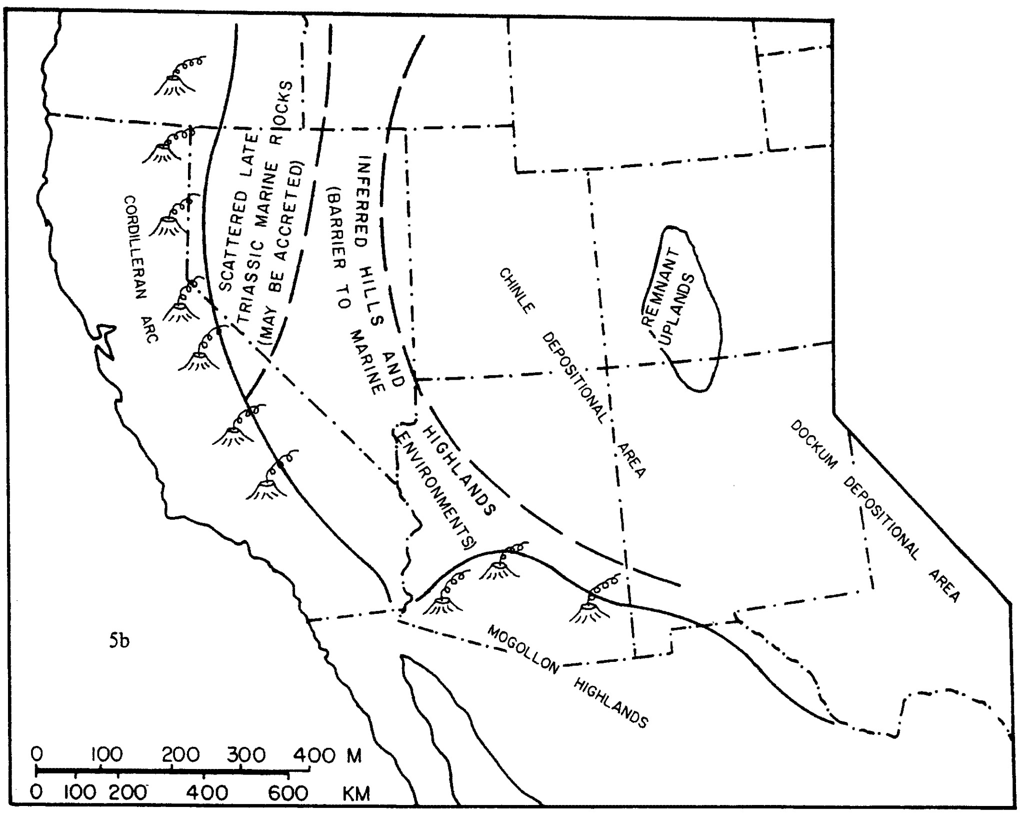
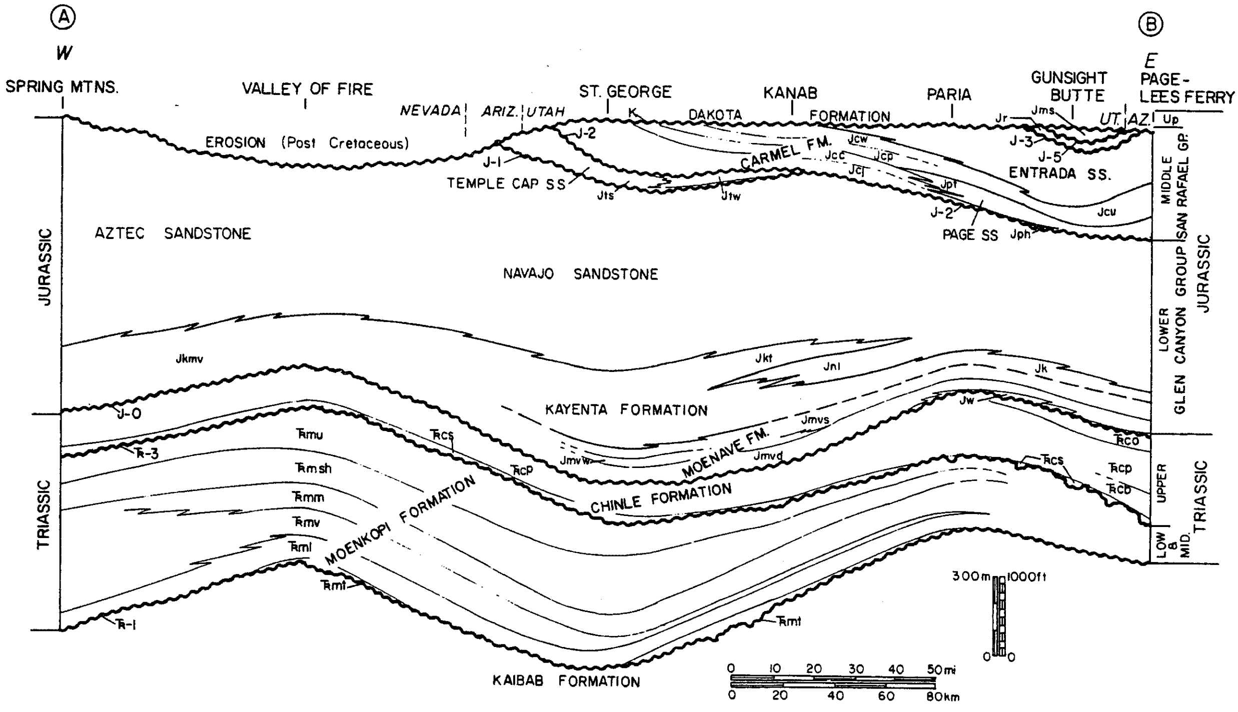


Figure 5. Map showing tectonic setting of (a) Moenkopi Formation and (b) Chinle Formation. Sonoma system is in thrust contact with rocks of miogeocline and may represent accreted terrane. Location and existence of volcanoes in Arizona is uncertain.



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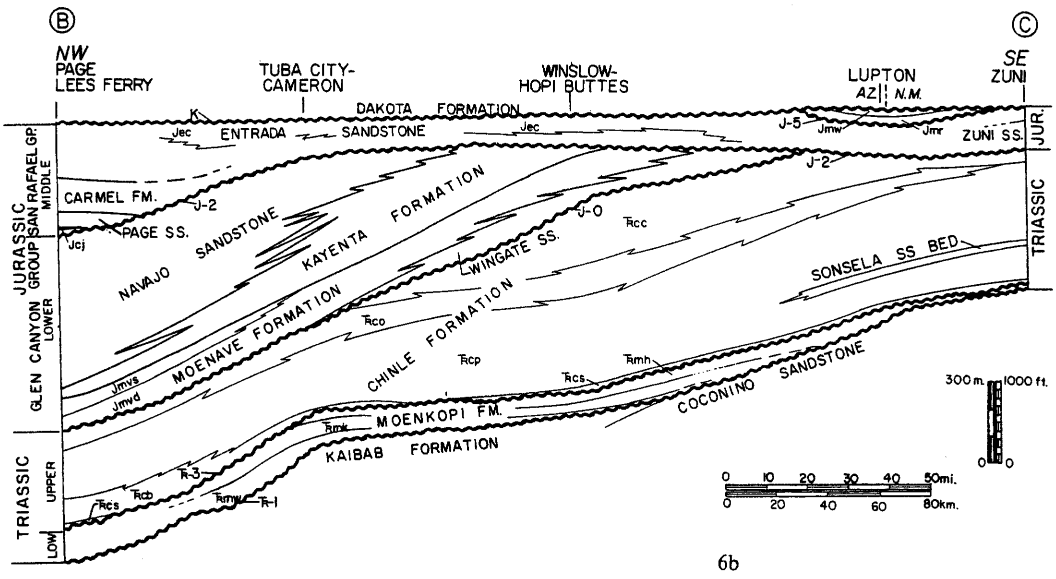

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Figure 6. Restored stratigraphic sections of Triassic and Jurassic rocks, southern Colorado Plateau and vicinity. Datum is sub-Cretaceous unconformity. See table 1 for abbreviations. Lines of section shown on figure 1.

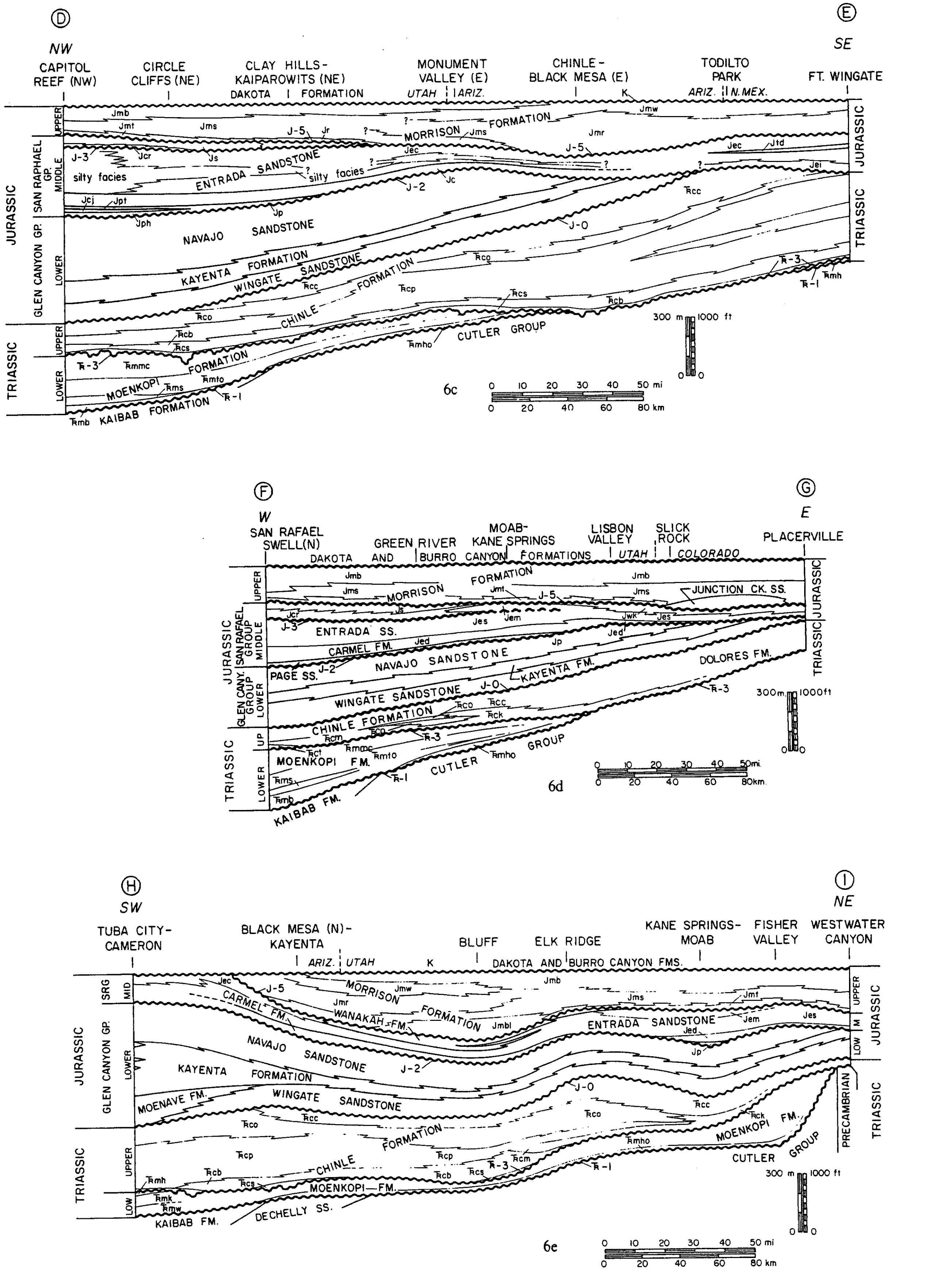

Figure 6. (continued)

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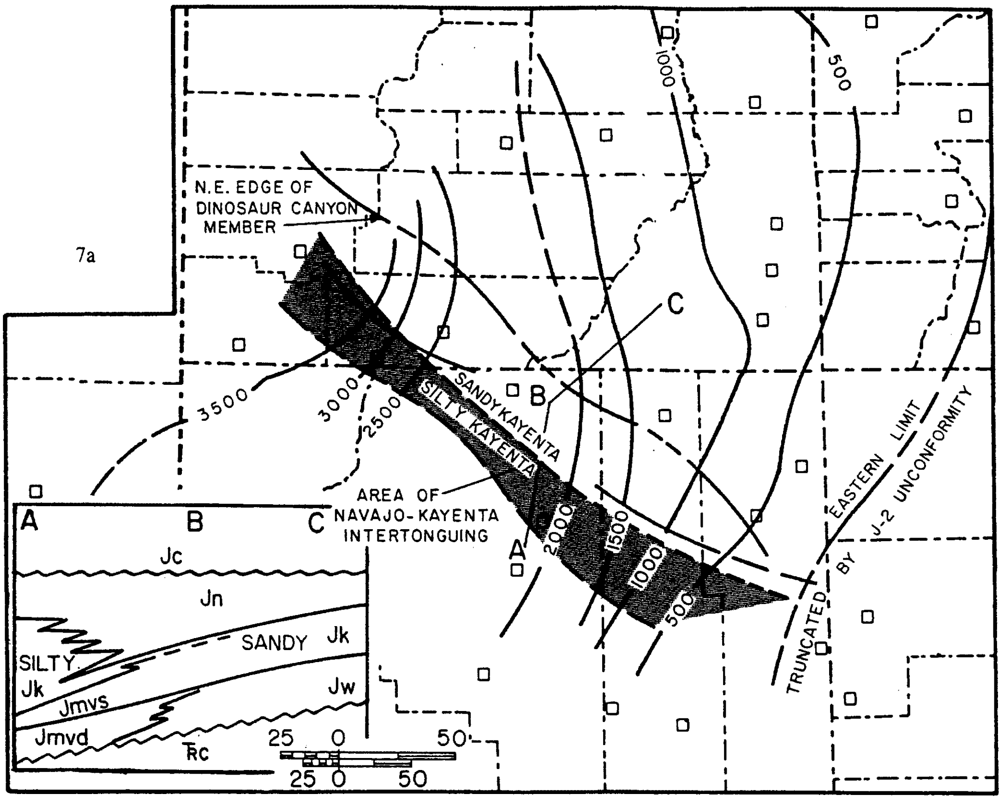

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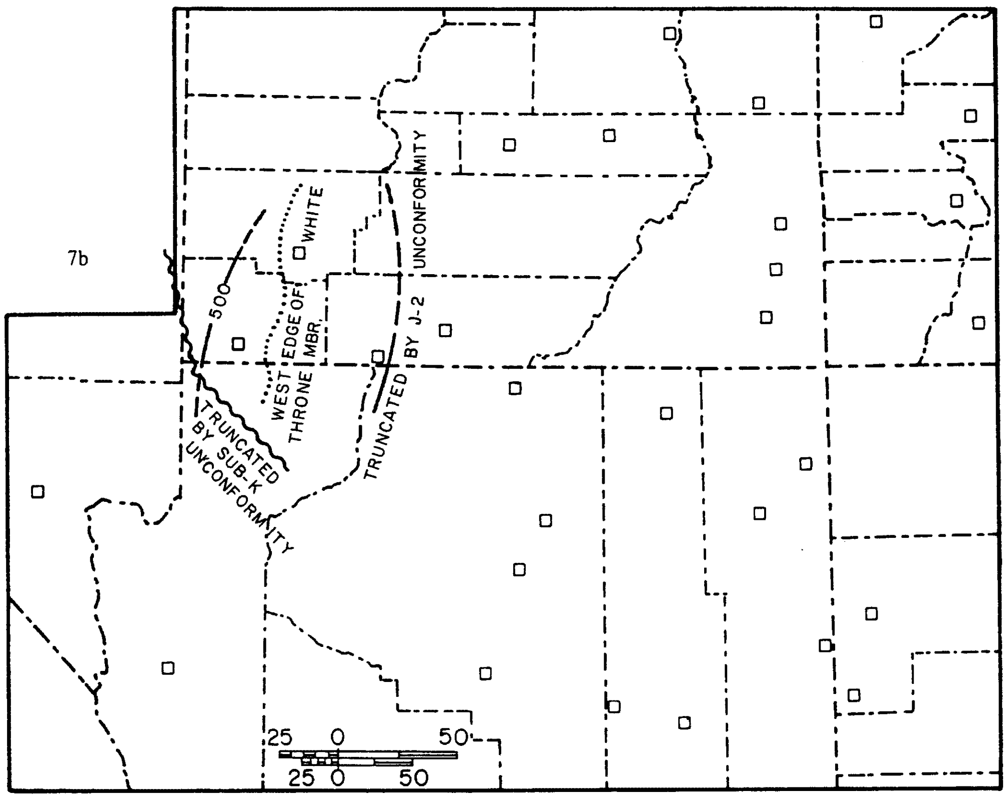
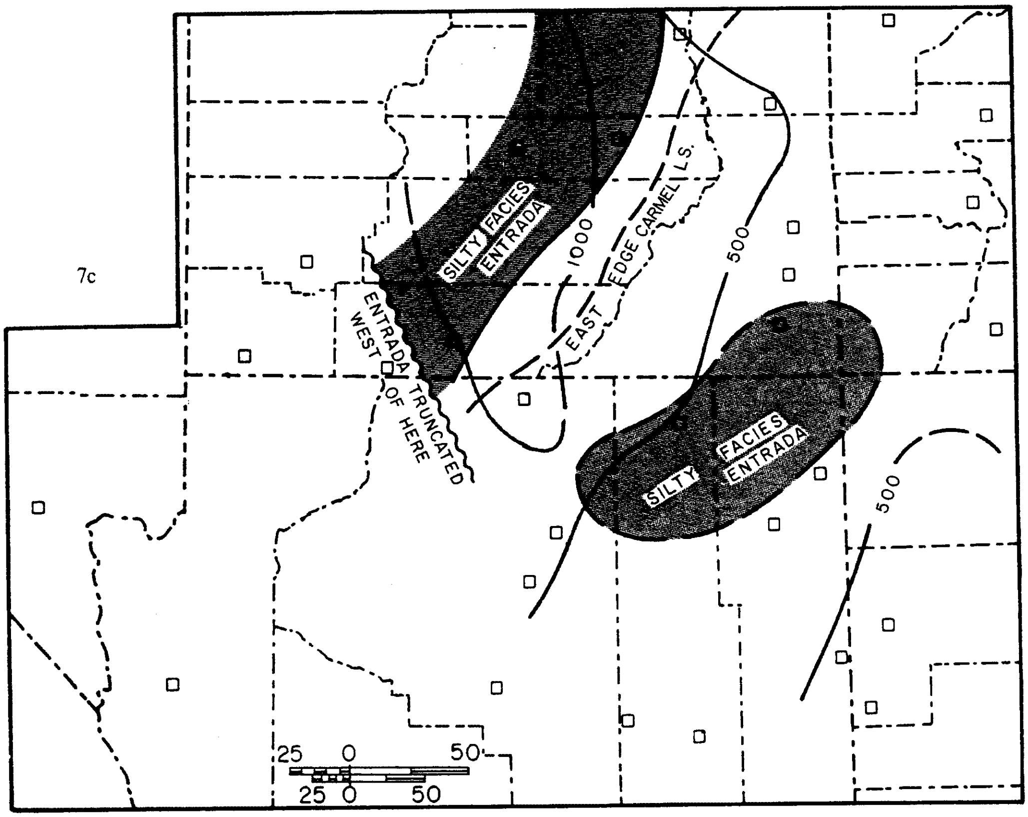


Figure 7. Isopach maps of the five Jurassic intervals discussed in text (compiled from many sources). Thicknesses given in feet. 7a—Glen Canyon Group. Insert cross section shows probable correlation of group from north-central Arizona to southeastern Utah. 7b—Temple Cap Sandstone. Truncation by sub-Cretaceous unconformity is inferred. 7c—Middle San Rafael Group including Page, Carmel, Entrada, Wanakah, and Todilto. 7d—Upper San Rafael Group including Summerville, Romana, Curtis, and Moab. 7e—Morrison Formation (isopachs after Craig and others, 1955, with thickness of Bluff and Junction Creek added).

7c



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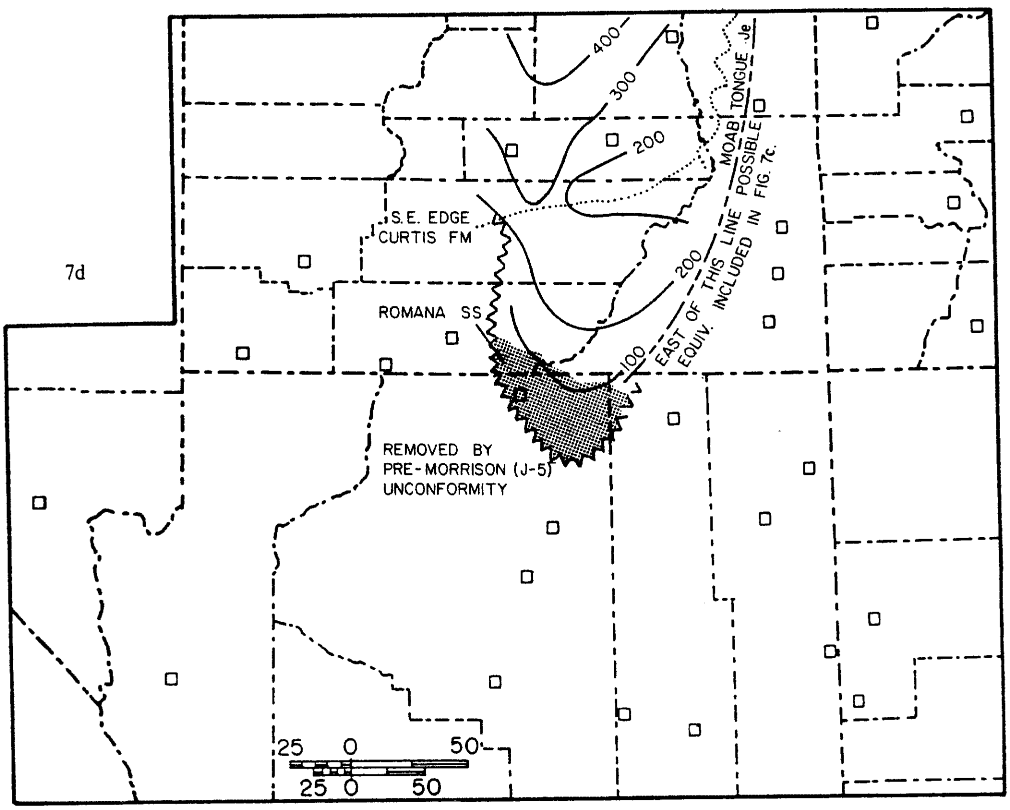

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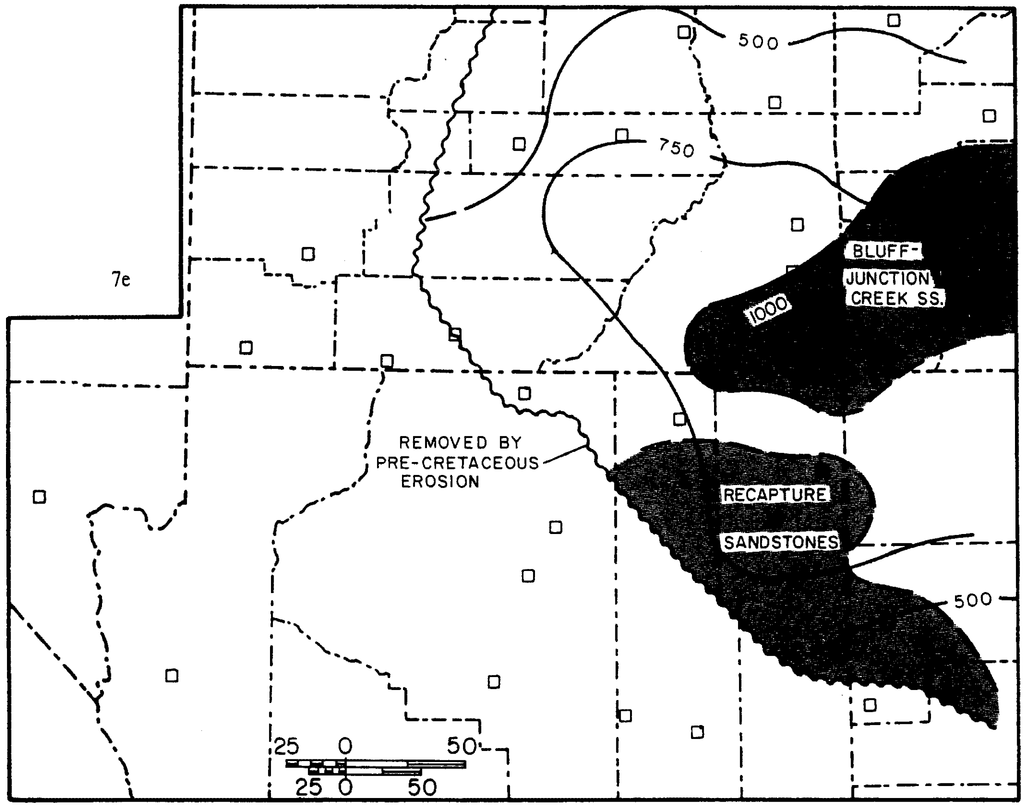

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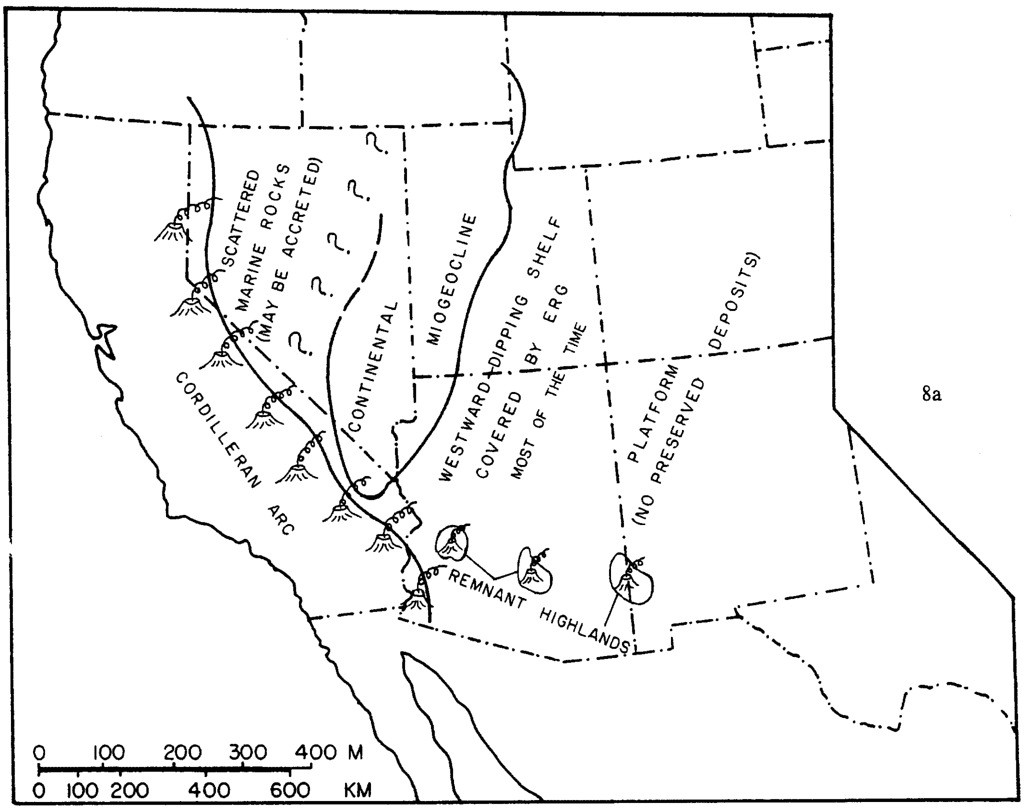
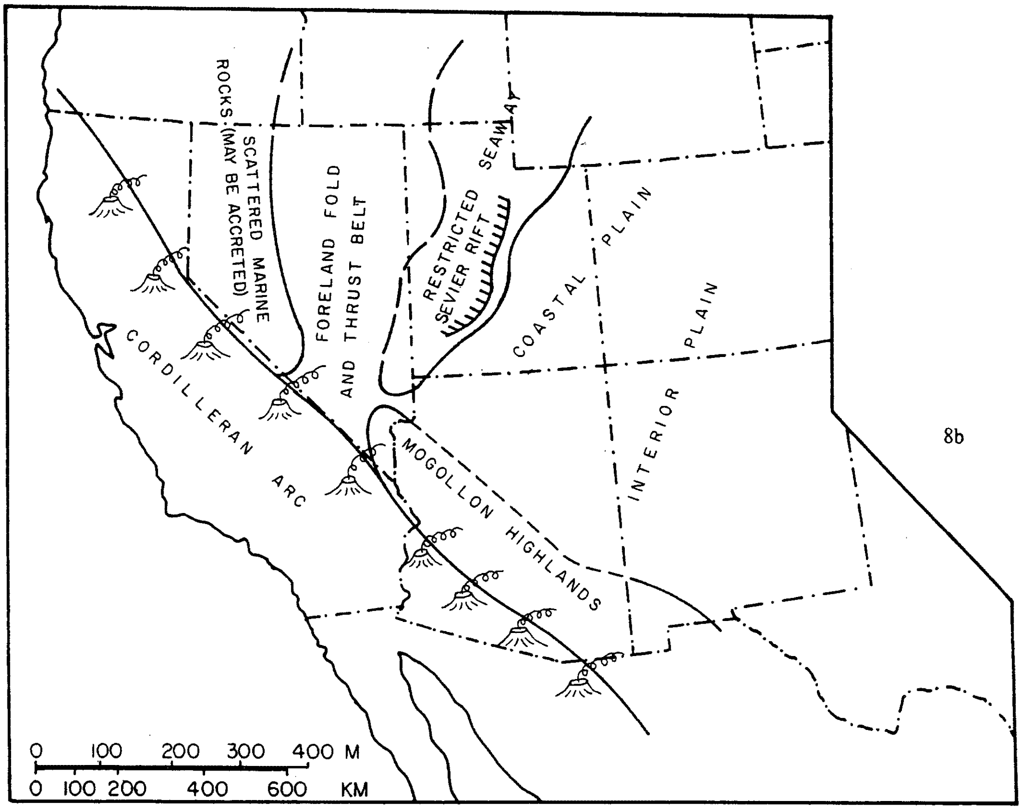


Figure 8. Maps showing Jurassic tectonic setting of Colorado Plateau during (a) Glen Canyon, (b) Middle San Rafael, and (c) Morrison deposition.



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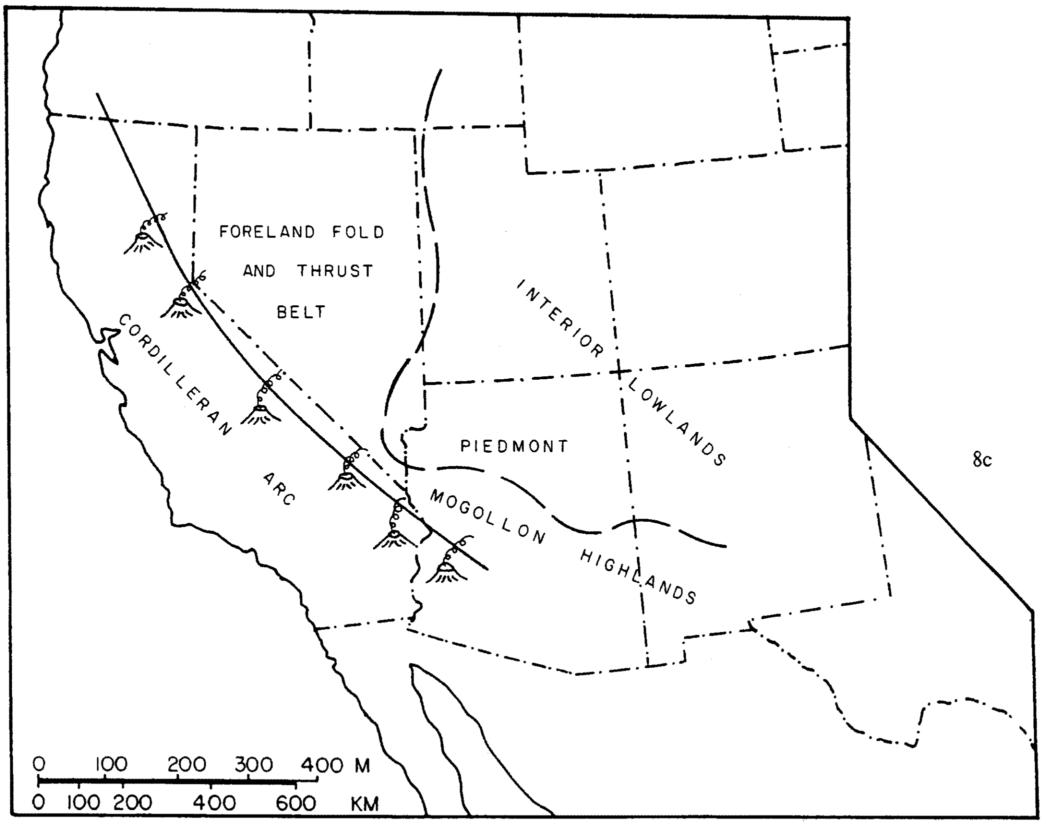

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Figure 8. (continued)

JURASSIC STRATIGRAPHY

Glen Canyon Group

Facies. The Glen Canyon Group consists of the Wingate Sandstone (restricted), the Moenave and Kayenta Formations, and the Navajo Sandstone. Recent detailed subregional to local studies by Edwards (1985) on the Moenave, Luttrell (1987) on the Kayenta, Hunter and Rubin (1983) and Rubin and Hunter (1983) on the Navajo, and Middleton and Blakey (1983) and Sargent (1984) on the Navajo-Kayenta intertonguing provide information for the following discussion:

1. East and north of the Echo Cliffs Upwarp, large-scale cross-stratified sandstone (CSS) of the Wingate Sandstone forms the lowest Glen Canyon deposits; southwestward near Tuba City the Wingate grades laterally into silty sandstone (STS), sandstone and mudstone (SSM), and red mudstone and siltstone (RMS) of the Dinosaur Canyon Member of the Moenave Formation (fig. 6).
2. The sandy facies of the Kayenta Formation and the Springdale Sandstone Member of the Moenave Formation form a broad sheet of cross-stratified lenticular sandstone (LCS) that covers the northern two-thirds of the area (fig. 7a).
3. South of a line from Cedar City, Utah, to Tuba City, Arizona, the upper Kayenta thickens rapidly to form the silty facies that consists primarily of bentonitic mudstone (BMS), red mudstone to siltstone (RMS), and ribbons and narrow sheets of cross-stratified lenticular sandstone (LCS). Much of this thickening is achieved through southward pinchout of Navajo tongues into the upper Kayenta.
4. Along this same line is a zone of intertonguing between the Kayenta and overlying Navajo Sandstone (Middleton and Blakey, 1983). Although intertonguing at much smaller scales is present elsewhere, it does not approach the magnitude of the zone along this line.
5. The top of the Glen Canyon Group consists of the Navajo Sandstone, undoubtedly one of the most voluminous pure quartz arenite formations in the geologic record.
6. Chiefly because of thickening of the Navajo, the Glen Canyon Group greatly increases in thickness to the west (fig. 7a).

Interpretation. The depositional environments of the Glen Canyon Group have long been known. The Wingate and Navajo are widespread eolian erg deposits, and the Moenave and Kayenta are chiefly fluvial. Detailed sedimentologic studies have added insight into the intricacies of their origin. Edwards (1985) explained the interrelations of flashy fluvial and eolian erg-margin deposition in the Moenave Formation of the Tuba City area. Luttrell (1987) documented multiple source terranes for the Kayenta, including a basement and reworked sedimentary source in Colorado and a volcanic source to the south of the Colorado Plateau. Sargent (1984) and Middleton and Blakey (1983) have added to the understanding of cyclic eolian, fluvial, and minor lacustrine deposition in the area of Navajo-Kayenta intertonguing. Hunter and Rubin (1983) and Rubin and Hunter (1983) have provided information concerning eolian depositional processes based on local sedimentologic studies of the Navajo.

Several questions remain. Why is there such a dominance of quartz arenite in the Glen Canyon group? Where did all the sand come from? Why, over much of the Colorado Plateau, are the two pure eolian quartz arenites separated by a less pure fluvial sequence?

Lower San Rafael Group

Introduction. Division and regional correlation of the San Rafael Group has been problematic over some areas of the Colorado Plateau (see reviews by Thompson and Stokes, 1970; Peterson, in press). Recognition of several major continental Jurassic unconformities and their regional correlation by Pipiringos and O'Sullivan (1978) have provided a basis for correlation. Five of these unconformities, from oldest to youngest J-0, J-1, J-2, J-3, J-5 (fig. 2), are present on the central and southern Colorado Plateau. Rocks assigned to the San Rafael Group lie between the J-1 and J-5 surfaces. In this paper, the group is divided as follows: lower San Rafael Group, pre-J-2, including the Temple Cap Sandstone; middle San Rafael Group, chiefly post-J-2, pre-J-3 but including some younger rocks east of the Monument Upwarp (this interval includes the Page Sandstone, Carmel Formation, Entrada Sandstone, and Wanakah Formation); and the upper San Rafael Group, post-J-3, pre-J-5, including the Curtis and Summerville Formations and related Romana Sandstone. West of the Monument Upwarp, the three parts are separated from each other and adjacent rocks by unconformities. East of the Monument Upwarp, an undeterminable amount of the middle portion is post-J-3 unconformity, as the unconformity surface is not recognizable here (figs. 2, 6, and 9).

Facies. The lower San Rafael Group consists of the Temple Cap Sandstone in southwestern Utah (Peterson and Pipiringos, 1979). Two members compose the formation. The White Throne Member is chiefly large-scale cross-stratified sandstone (CSS) and dominates the eastern and upper portions of the Temple Cap (table 2). The Sinawava Member comprises red mudstone to siltstone (RMS) and bentonitic mudstone (BMS) and forms the western and lower portions of the unit (fig. 6). The formation probably was truncated by pre-Cretaceous erosion in extreme southwestern Utah and adjacent parts of Arizona and Nevada (fig. 7b).

Interpretation. Peterson and Pipiringos (1979) suggested a correlation of the Temple Cap with the Gypsum Spring Formation of Wyoming. The margins of the Gypsum Spring seaway probably extended south along the

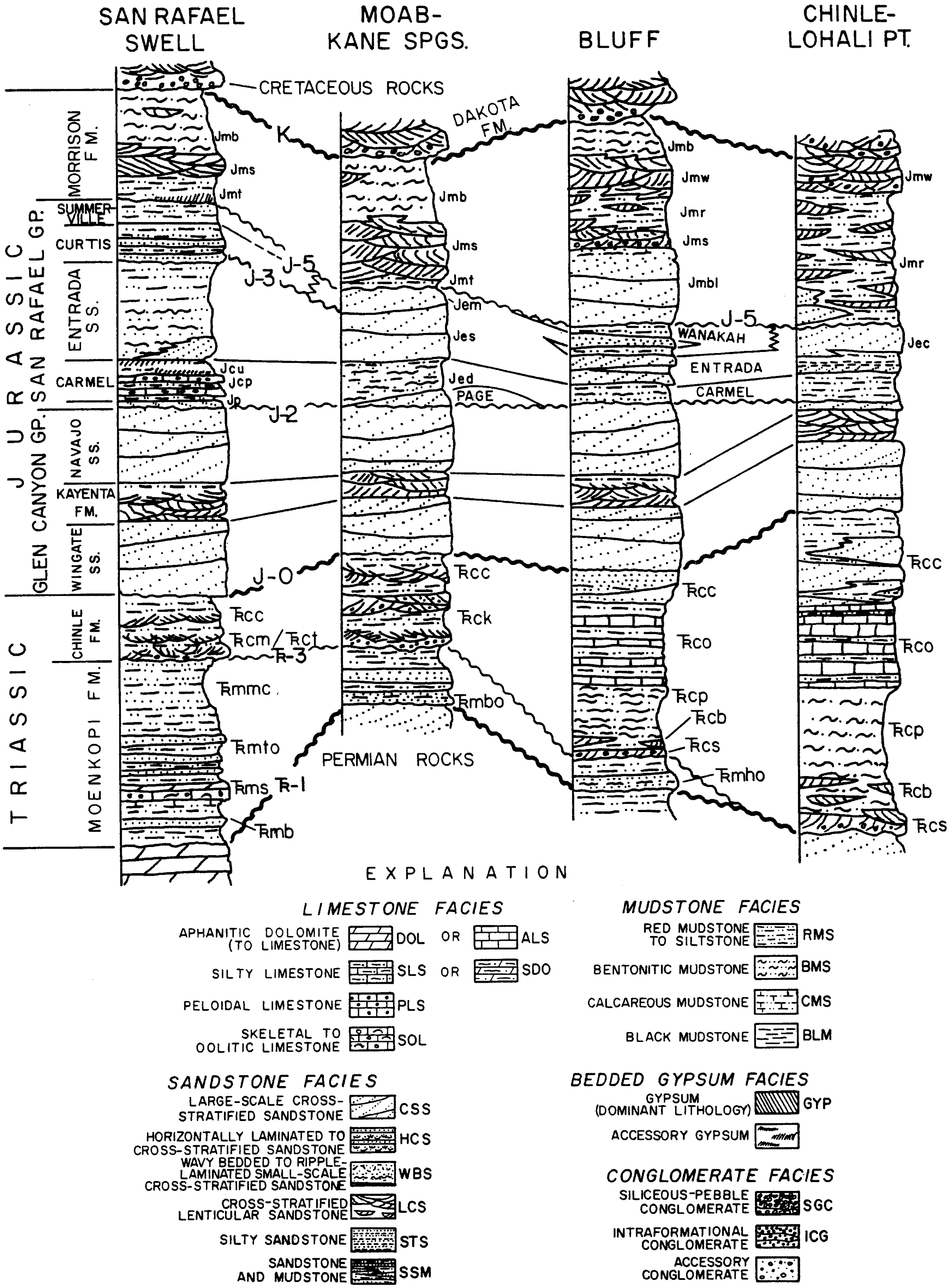

Figure 9. Selected Jurassic and Triassic stratigraphic columns from southern Colorado Plateau. Datum is J-2 unconformity.

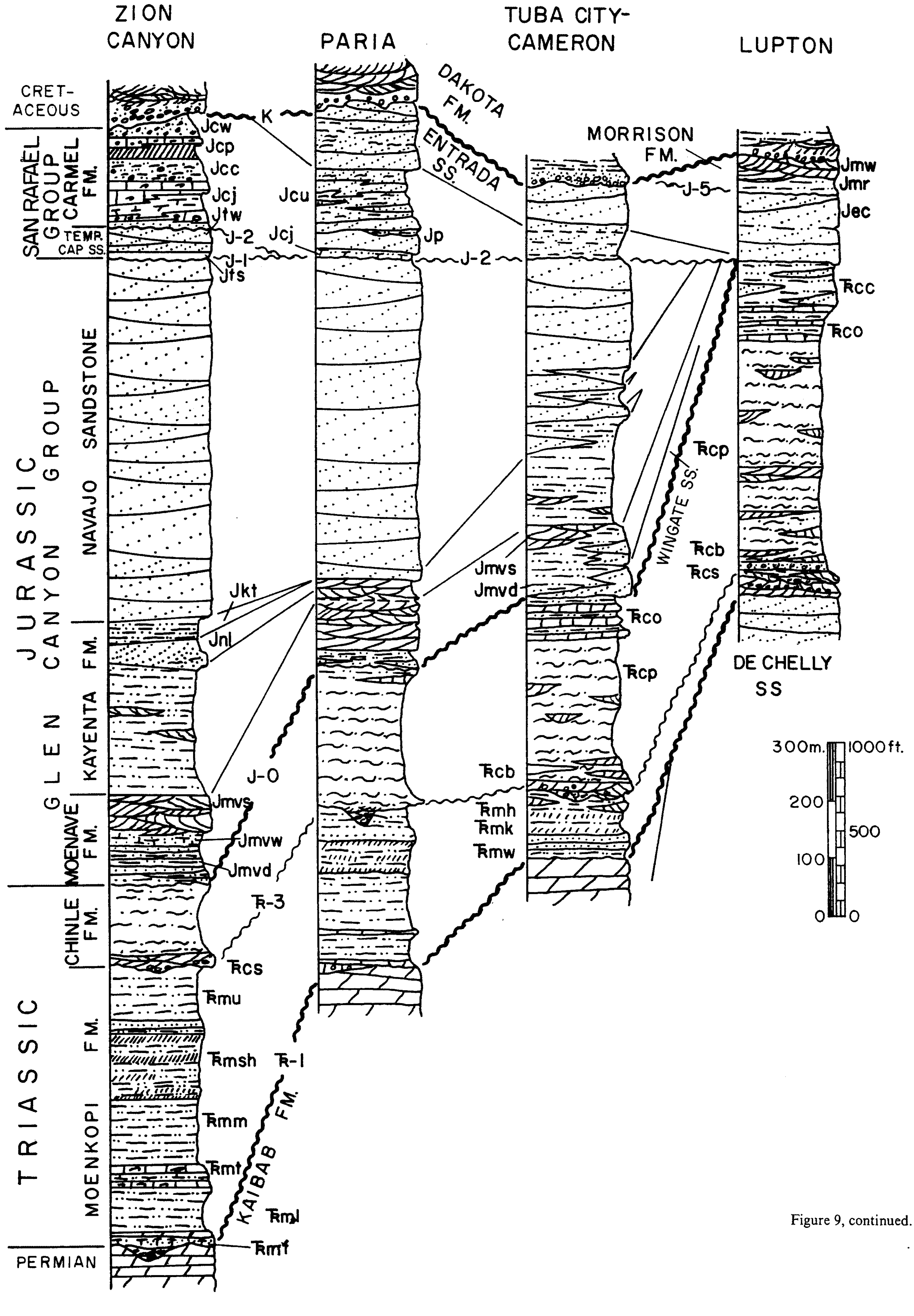

Figure 9, continued.

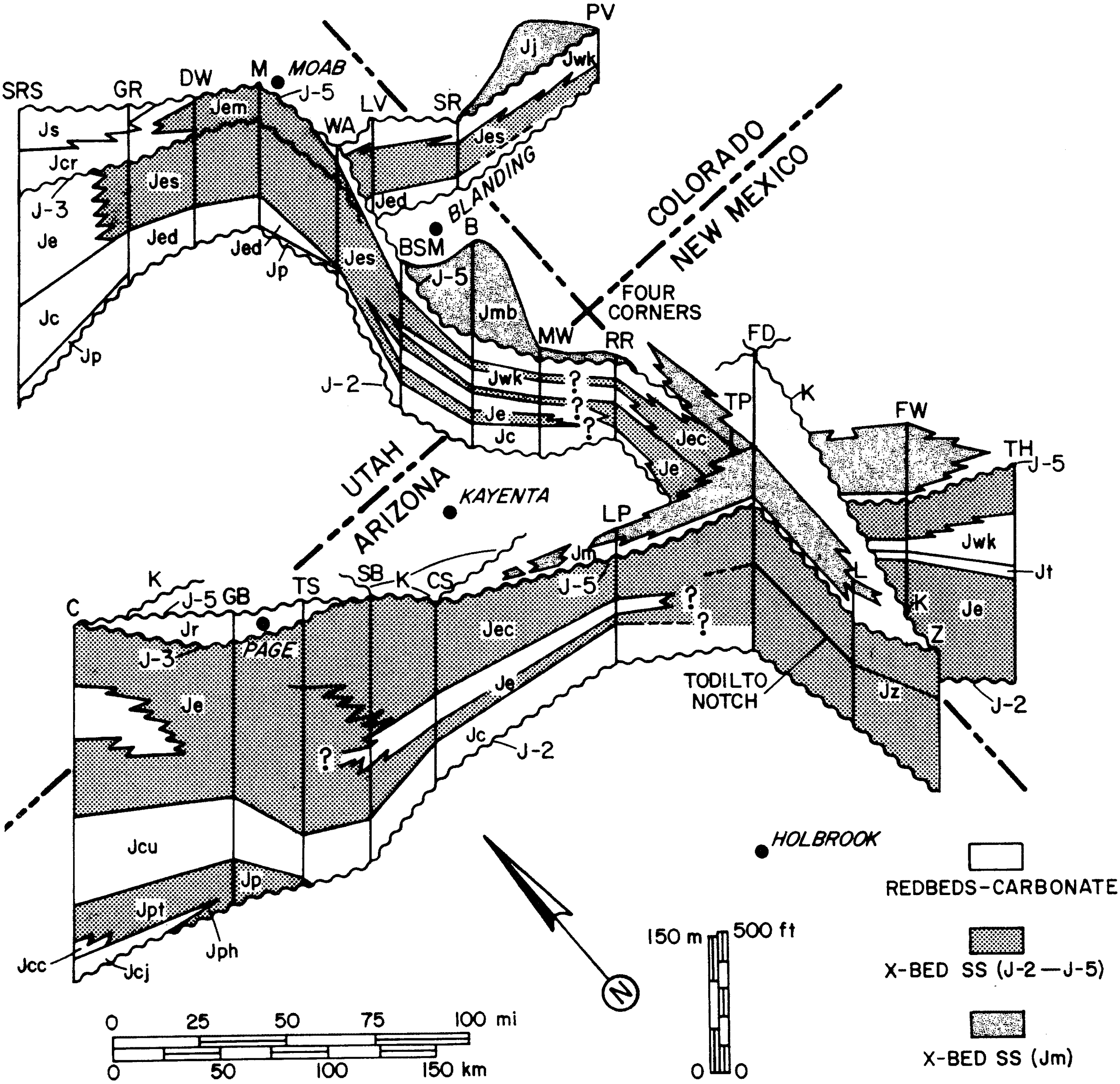

Figure 10. Fence diagram of Jurassic rocks between J-2 and J-5 unconformities also showing distribution of major eolian rocks above the J-5 unconformity. Sources of data include Blakey and others (1983), O'Sullivan (1978, 1980a, 1980b, 1981a, 1981b). Locality abbreviations: SRS-San Rafael Swell, GR-Green River, DW-Dubinky Well, M-Moab, WA-Wilson Arch, LV-Lisbon Valley, SR-Slick Rock, PV-Placerville, BSM-Black Steer Mesa, B-Bluff, MW-Mexican Water, RR-Rough Rock, TP-Todilto Park, FD-Ft. Defiance, FW-Ft. Wingate, TH-Thoreau, C-Cannonville, GB-Gunsight Butte, TS-Tsai Skizzi Rock, SB-Square Butte, CS-Cow Springs, LP-Lohali Point. Note: tops of fence posts show geographic locality.

west edge of the Colorado Plateau. The Sinawava Member formed along the coastal plain, probably during maximum transgression. Eolian deposits of the White Throne Member formed during regression.

Middle San Rafael Group

Introduction. Undoubtedly, the most complex sequence in Mesozoic rocks on the Colorado Plateau includes the interval between the J-2 and J-3 (or J-5 east of Monument Upwarp) unconformities. This interval, herein called the middle San Rafael Group, includes the Page Sandstone, Carmel Formation, Entrada Sandstone, and Wanakah Formation. A series of detailed correlation charts by O'Sullivan (1978, 1980a, 1980b, 1981a, 1981b) provides a basis for regional correlation. A brief discussion of correlations used in this report will be followed by facies description and interpretation.

Correlation. Correlation of the middle San Rafael Group west of the Monument Upwarp is clear (fig. 6). Correlation south and east of the upwarp is still in doubt.

O'Sullivan (1978, 1980a, 1980b, 1981a, 1981b) published correlations that show the relations of the Entrada and Wanakah in eastern Utah and western Colorado and south into Arizona to near the town of Chinle (fig. 6). Correlation in northeastern Arizona and adjacent parts of New Mexico is still uncertain. Major facies changes occur over short distances and critical sections are missing because of erosion across the Defiance Upwarp. The most critical problem involves correlation of the so-called "Cow Springs Sandstone." The Cow Springs Sandstone is a cross-stratified bleached sandstone that lies between the Entrada Sandstone and Dakota Formation (Cretaceous) on the north side of Black Mesa Basin southwest of Kayenta, Arizona. The Cow Springs was correlated with similar bleached sandstone units that intertongue with the Summerville Formation (Wanakah Formation as used herein) and Morrison Formation. Generally, any bleached cross-stratified sandstone at or near the top of the San Rafael Group in Arizona and New Mexico has been assigned to the Cow Springs. Green (1975) recognized three Jurassic depositional units in the southern San Juan Basin: (1) the San Rafael Group, (2) the lower Morrison including a so-called "Cow Springs Tongue," and (3) an upper Morrison. Peterson and Condon (1984) showed that the Cow Springs entirely underlies the J-5 (pre-Morrison) unconformity and can be traced into the Lake Powell region where it underlies the J-3 (pre-Curtis Formation) unconformity and is therefore older than the Morrison Formation. Thus the Cow Springs is bounded on top by the same unconformity that elsewhere bounds the top of the Entrada Sandstone. Peterson believes that the type section of the Cow Springs Sandstone is an integral part of the Entrada and intends to assign it as a member of the Entrada Sandstone (Peterson, in press). Peterson correlates the type Cow Springs eastward, granted through discontinuous outcrops, to the eastern side of the Defiance Upwarp where it overlies the Todilto Limestone (also pre-J-5) and is overlain unconformably by the Morrison Formation. Peterson and Condon (1984) reported sedimentologic differences between Cow Springs and Morrison eolian units including textural and paleocurrent contrasts. Consequently, the term Cow Springs should be restricted to Entrada-equivalent rocks and not used for similar but younger eolian sandstone strata in the Morrison. A similar conclusion was reached by Condon and Huffman (1984). My own observations confirm this correlation and restriction of Cow Springs. Figure 10 shows this correlation. Therefore the Cow Springs in the eastern Defiance Upwarp and northern Zuni Uplift represents a cross-stratified sandstone facies of the Wanakah Formation. Similar well-documented relations exist between the upper Entrada and Wanakah Formations (fig. 10) in southeastern Utah and adjacent parts of Colorado (O'Sullivan, 1980a). South of Lupton, Arizona, and the Zuni Uplift, the entire Jurassic sequence comprises cross-stratified sandstone equivalent to the Entrada Sandstone, including the Cow Springs Member (Condon and Huffman, 1984). This unit has generally been called the Zuni Sandstone (Anderson, 1983).

O'Sullivan (1980a) made two other major stratigraphic changes for Jurassic rocks on the east side of the Monument Upwarp: (1) Strata previously assigned to the Summerville Formation were reassigned to the Wanakah Formation; (2) the Bluff Sandstone, which overlies the J-5 unconformity, was reassigned as a member of the Morrison Formation. With these changes, a much clearer correlation of Middle and Upper Jurassic rocks results (fig. 10).

Although local details remain to be solved, the following summarizes current thinking concerning Jurassic stratigraphy of the Four Corners region:

1. The Cow Springs Sandstone is a pre-Morrison deposit that will be assigned to the Entrada Sandstone (Peterson, in press).
2. The Bluff Sandstone is a member of the Morrison Formation (O'Sullivan, 1980a) and is younger than the Cow Springs.
3. The Recapture Member of the Morrison Formation contains significant cross-stratified sandstone that is younger than Cow Springs and probably younger than most of the Bluff Sandstone Member (fig. 10).
4. The Zuni Sandstone is a local term used in the Zuni, New Mexico area and is equivalent to the Entrada Sandstone.
5. Thus defined, there are three lithologically similar but stratigraphically distinct units present in the region (figs. 2, 6c, 6e, 9, and 10). Note also that these figures correlate the Wanakah Formation of the northern Four Corners region into adjacent areas of Arizona and New Mexico.

Facies. Numerous facies are present in the middle San Rafael Group strata (fig. 6). The interfingering Carmel Formation and Page Sandstone comprise limestone (SLS, PLS, SOL), redbeds (STS, SSM, EMS), calcareous mudstone (CMS), gypsum (GYP), and sandstone (CSS, HCS, WBR). Huge boulders (up to 5 m in diameter) of rhyolitic tuff and pebbles of granite rock fragments crop out in the Carmel Formation along the Paria River south of Paria, Utah. These exotic clasts occur in the upper member of the Carmel Formation in bentonite-rich silty sandstone and sandy red mudstone. The Entrada contains chiefly sandstone (CSS, HCS, WBR) with subordinate redbeds and the Wanakah comprises sandstone, siltstone, and mudstone (WBR, STS, SSM, and RMS). The Todilto Limestone consists of aphanitic limestone (ALS) and gypsum.

Interpretation. The Carmel Formation formed in and adjacent to a shallow restricted sea (Voorhees, 1978; Geesaman, 1979; Blakey and others, 1983). The exotic rhyolitic tuff and granitic clasts signify volcanic activity and basement terrane associated with crustal uplift to the southwest. The location and nature of this terrane are currently unknown although the size of the clasts suggests closer proximity to the Colorado Plateau than previously thought. The Page represents chiefly coastal and inland dune deposits (Caputo, 1980). The Entrada was deposited in a large erg-and-sabkha complex that covered the Colorado Plateau, bordering a large marine embayment that covered much of Wyoming and Montana (Kocurek and Dott, 1983). In the study area, eolian dunes formed a band 100 km or more wide from Moab to Page. Another similar band extends southward along the Utah-Colorado and Arizona-New Mexico borders into west-central New Mexico. Both dune fields grade in all directions into adjacent silty sandstone or redbeds. A large area of silty sandstone makes up most of the Entrada in northeastern Arizona and probably represents sabkha and desert-lake environments. Another large lacustrine and sabkha system in New Mexico lay to the east of the Entrada erg and was the site of Todilto and Wanakah deposition.

Upper San Rafael Group

Introduction. The upper San Rafael Group consists of the Curtis Formation and Summerville Formation, rests on the J-3 unconformity, and is present west of the Monument Upwarp. Part of the Curtis passes eastward into the Moab Tongue of the Entrada Sandstone (figs. 6 and 10), and the Summerville is truncated by the J-5 unconformity (O'Sullivan, 1980b). The Moab Tongue can be traced southward along the eastern flank of the Monument Upwarp where it grades into the upper Slick Rock Member of the Entrada, which further south grades into the upper part of the Wanakah Formation. Thus the Wanakah and Entrada in the southeastern part of the study area contain Summerville and Curtis temporal deposits. Peterson (1973; in press) has recognized a sandstone between the J-3 and J-5 unconformities in the Kaiparowits Basin. Named the Romana Sandstone, it represents a sandy facies of the Summerville Formation.

Facies. The Curtis Formation comprises chiefly light-gray horizontally laminated to cross-stratified sandstone (HCS) and calcareous to silty mudstone (CMS; Smith and others, 1963). The Summerville Formation is a heterolithic redbed unit containing facies SSM and RMS. In the Henry Mountains, Summerville-like strata above the J-5 unconformity are now placed in the Morrison Formation (Klockenbrink, 1979). The Romana Sandstone consists primarily of facies HCS.

Interpretation. The Curtis Formation has long been interpreted as a shallow-marine and shoreline deposit and the overlying Summerville as tidal flat and restricted marine (Smith and others, 1963). Between the Green and Colorado Rivers, the Curtis rapidly grades laterally first into redbeds and then into eolian deposits of the Moab Tongue of the Entrada Sandstone (figs. 6 and 10). The Wanakah and Entrada equivalents farther southeast have been discussed in the previous section. Peterson (1973) suggested that the Romana Sandstone, a sandy facies of the Summerville, formed in shoreline and eolian environments.

Morrison Formation

Facies. The Morrison Formation forms an extensive coarse- and fine-grained terrigenous clastic sheet northeast of a line from east of Cannonville, Utah, to Zuni, New Mexico (figure 7). The formation generally coarsens toward this line (Stokes, 1944; Craig and others, 1955; Harshbarger and others, 1957) although in detail there are exceptions to this statement. These three papers remain as the sources of regional data. More localized reports by Saucier (1967), Corken (1979), Klockenbrink (1979), Jensen (1982), and Peterson (1980; 1984a) provide more detailed interpretation. The following salient points apply to the formation in the area of study:

1. Seven members are recognized in the Four Corners area and three most other places.
2. The Salt Wash Member forms a broad alluvial complex that coarsens westward toward the northwestern Kaiparowits and Henry Mountains regions; facies LCS and subordinate siliceous-pebble conglomerate (SCG) make up most of the unit.
3. Along the New Mexico-Arizona state line the Salt Wash Member grades into red silty sandstone (STS), sandstone and mudstone (SSM), red mudstone to siltstone (RMS), and associated lenticular cross-stratified sandstone (LCS) of the Recapture Member (fig. 6). In the Defiance region and northern Zuni Uplift area large-scale cross-stratified sandstone (CSS) forms an important component of the Recapture Member (Condon and Huffman, 1984; Peterson, in press) (figs. 6 and 10). This has previously been miscorrelated with the Cow Springs Sandstone (Peterson and Condon, 1984).
4. In the Kaiparowits and Henry Mountains regions, the lower Salt Wash grades laterally into the Tidwell Member (Klockenbrink, 1979; Peterson, 1984), a unit soon to be formalized as a member of the Morrison (Peterson, in press). The Tidwell, which comprises facies STS, SSM, RMS, CMS, CSS, and GYP, is recognized over large portions of the central Colorado Plateau.
5. The Westwater Canyon Member is another alluvial deposit, with siliceous pebbles in sandstone (LCS) most abundant near Gallup, New Mexico (Turner-Peterson and others, 1980) and arkosic cross-stratified lenticular sandstone (LCS) present farther north (Corken, 1979). The member gradually grades northward into bentonitic mudstone (BMS) of the Brushy Basin Member (fig. 6).
6. The Brushy Basin likely contains finer grained temporal deposits of parts of the other coarse-grained members.
7. South of the Zuni-Cannonville line, the Morrison has been removed by pre-Cretaceous erosion (Peterson, 1984).

8. The Bluff Sandstone Member of the Morrison Formation forms the base in the Four Corners region. The Bluff Sandstone is the lateral equivalent of the Junction Creek Sandstone in Colorado (fig. 6). Both are chiefly facies CSS and associated HCS and WBR.

Interpretation. The Morrison Formation formed in a continental setting in which fluvial, fluvial-lacustrine, and eolian depositional systems prevailed (Stokes, 1944; Craig and others, 1955; Harshbarger and others, 1957). Eolian environments are recognized in parts of the Bluff Sandstone Member and equivalent Junction Creek Sandstone (O'Sullivan and Maberry, 1975). In my opinion, the marine trace fossils reported in their paper need further study before marine origin can be documented. Similar trace fossils occur in undoubtedly eolian deposits in several outcrops of Permian and Jurassic rocks on the Colorado Plateau (Blakey and Middleton, 1984). Large-scale cross-stratified sandstone in the Recapture Member has been interpreted as eolian (Harshbarger and others, 1957; Corken, 1979; Condon and Huffman, 1984). The eolian deposits in the Recapture represent a small erg in the Defiance region that formed as westerly winds blew sand off the adjacent Salt Wash alluvial plain.

An extensive lacustrine system developed in the Henry Basin region during initial Morrison deposition and is represented by mudstone, thin sandstone, and bedded gypsum of the Tidwell Member (Klockenbrink, 1979; Peterson, 1984, in press). Small eolian deposits occur in the Tidwell in the Henry Mountains and Kaiparowits regions (Peterson, 1980, 1984) and along the south margin of the Abajo Mountains.

The broad clastic wedges that compose the Salt Wash, Recapture, and Westwater Canyon Members have been compared to the large alluvial fans present today on the plains south of the Himalaya Mountains of India (Galloway, 1978). However, Peterson (1984) contended that such a model is not applicable to Morrison deposition. Braided streams dominated proximal and medial portions of the Morrison complexes (Corken, 1979; Peterson, 1984) and meandering streams were present on distal portions (Peterson, 1984). Small lakes punctuated the alluvial plains (Peterson, 1980, 1984). The Brushy Basin Member formed initially in the distal portions of the above systems and then later as broad lakes and lacustrine mudflats. These broad saline-alkaline flats contain scarce scattered fluvial channels that extended, at times, various distances into the system (Peterson, 1984).

Pre-Cretaceous Erosion

Six major continental unconformities interrupted Triassic and Jurassic deposition across the Colorado Plateau (Pipiringos and O'Sullivan, 1978). Although the duration and amount of underlying strata removed varied greatly, most appear to be related to tilting and uplift and, on a regional extent, are low-angle unconformities (fig. 6). Direction of tilt varies between the adjacent unconformities, and this variance probably represents a period of tectonic adjustment on the Colorado Plateau from a westward slope dominant during Paleozoic and Early Triassic to a northeastward slope dominant during Cretaceous and Cenozoic time. The northeastward tilt was finalized during the development of the J-5 (pre-Morrison) unconformity and continued with the formation of the pre-Cretaceous unconformity. Southwest of a subtle but important hingeline that ran from Cannonville, Utah, to Zuni, New Mexico, appreciable amounts of the Triassic and Jurassic rocks were removed prior to deposition of the Cretaceous Dakota Formation and equivalent strata (fig. 6). In general, 500 to 2,000 m of strata were removed from the Little Colorado River valley, Flagstaff, and Grand Canyon regions where Cretaceous rocks unconformably overlie Permian rocks. The presence of extremely low-angle discordances at the base of Cretaceous rocks suggests that the southern Colorado Plateau was a gently northeast-dipping ramp across which Dakota and related deposits were transported; however, the coarse nature of these sediments and their arkosic to lithic character in southern Utah and northeastern Arizona suggest the presence of large mountain ranges south and west of the plateau edge.

PALEOGEOGRAPHY

The paleogeography summary presented here covers the salient points of Triassic and Jurassic depositional history. At least one map is shown for each interval. The maps are generally derived directly or modified slightly from recent publications and theses.

Moenkopi Formation

Shallow-marine and coastal-plain deposition on a westerly dipping plain continued patterns established during Paleozoic time. Figure 11 shows the hypothetical paleogeography during maximum extent of a delta that developed during deposition of the Torrey Member (Blakey, 1974; Abendshein, 1978); additional maps of Moenkopi paleogeography during different intervals are shown by Blakey (1974).

Chinle Formation

Following formation of the TR-3 unconformity, major changes in paleoslope are evident. Initial Chinle streams flowed northwestward (Blakey and Gubitosa, 1983, 1984), but patterns are more complex later in the formation and exhibit roughly centripetal patterns around the Chinle depocenter in northeastern Arizona (Stewart and others, 1972b). Figure 12 shows the hypothetical paleogeography during Petrified Forest-early Owl Rock deposition; additional maps during different Chinle intervals are shown by Blakey and Gubitosa (1983).

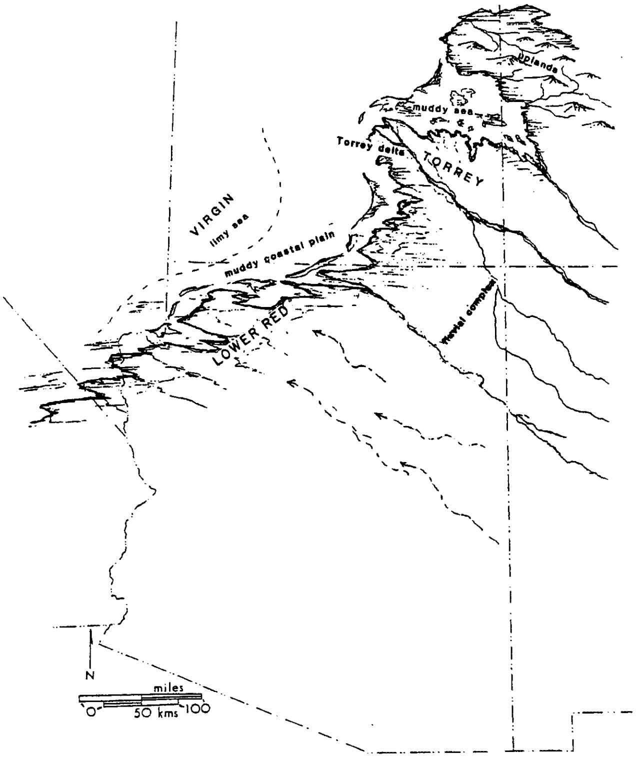

Figure 11. Hypothetical paleogeography during deposition of Torrey Member of Moenkopi Formation (after Blakey, 1974).

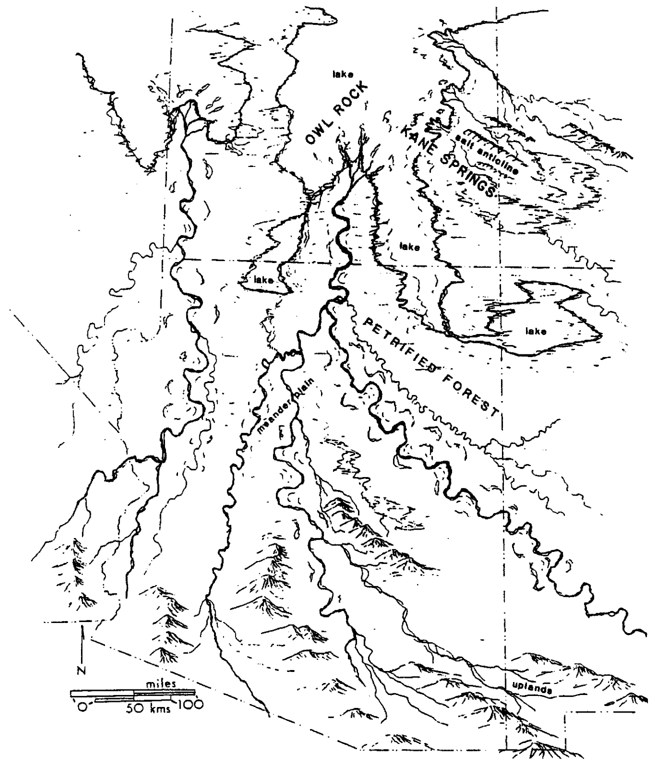

Figure 12. Hypothetical paleogeography during deposition of middle part (Petrified Forest time) of Chinle Formation (after Blakey and Gubitosa, 1983).

Glen Canyon Group

Isopachs (fig. 7) suggest a repetition of Paleozoic and Moenkopi trends, and this is partly confirmed by Moenave and Kayenta stream-flow directions (Sargent, 1984; Edwards, 1985; Luttrell, 1987). Figure 13 shows inferred fluvial Moenave and eolian Wingate relations, and figure 14 shows the relations of the fluvial Springdale Sandstone, Kayenta Formation, and eolian Navajo Sandstone.

Lower San Rafael Group

Details of Temple Cap Sandstone deposition are difficult to reconstruct because the formation is exposed only in a small area of southwest Utah. Therefore tectonic relations and depositional slope are unclear. Sabkha and evaporite deposits to the west bordered by eolian dunes to the east (fig. 15) suggest a continuation of the slope that was developed during deposition of the Glen Canyon Group.

Middle San Rafael Group

The Carmel Formation, Page Sandstone, and early Entrada Sandstone were deposited on the southern and eastern margin of a long, often restricted Jurassic seaway (Blakey and others, 1983). Uplift to the south follows Chinle trends but the broad west- to northwest-sloping coastal plain across much of Utah and northeastern Arizona follows Moenkopi and Glen Canyon trends. Page and lower Carmel depositional systems are shown in figure 16, and Entrada erg development is shown in figure 17.

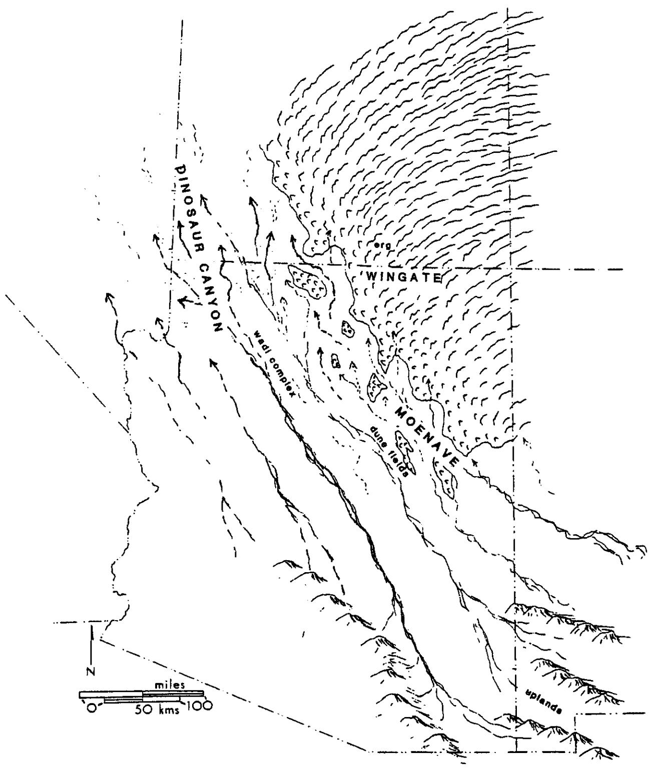

Figure 13. Hypothetical paleogeography during deposition of Moenave Formation and Wingate Sandstone.

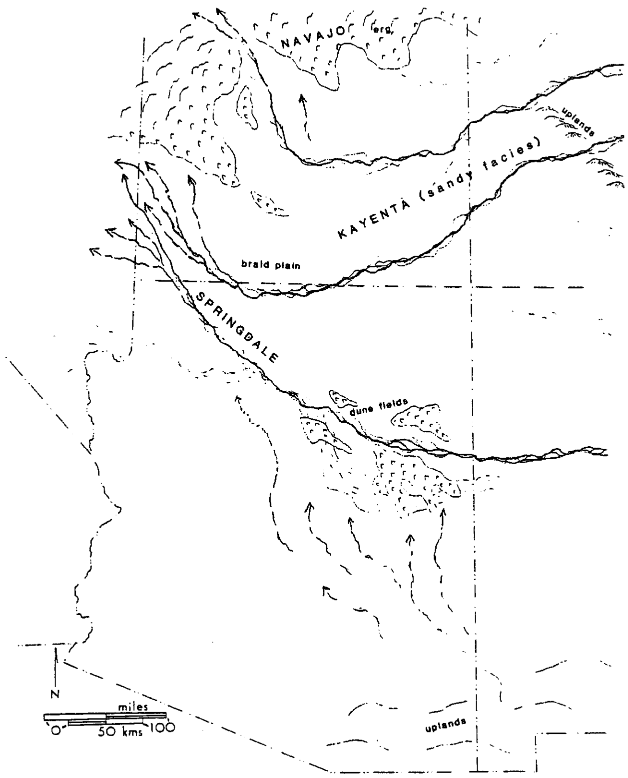

Figure 14. Hypothetical paleogeography during deposition of the Kayenta Formation.

Upper San Rafael Group

The upper San Rafael shows a continuation of previous trends. A long, narrow restricted seaway entered the region from the north. The Summerville and Curtis Formations and Moab Tongue of the Entrada Sandstone formed within the seaway and on its margins (figure 18).

Morrison Formation

Uplift of regions bordering the southwestern and western margins of the Colorado Plateau was firmly established during Morrison time and generated major northeastward-flowing streams. Local downwarps on the Colorado Plateau were the site of lacustrine (Peterson, 1984) and eolian deposition (fig. 19). Large alluvial complexes then spread northeastward across the Colorado Plateau (fig. 20). The pronounced tectonic uplift to the southwest dominated southwestern geologic history for almost 100 million years, through early Tertiary time.

ACKNOWLEDGMENTS

This paper has benefited greatly from thorough reviews by Robert B. O'Sullivan and Fred "Pete" Peterson, both of the U.S. Geological Survey in Denver, Colorado. Special thanks are due Pete for keeping me abreast of the latest flurry of work, much of it still unpublished, on the

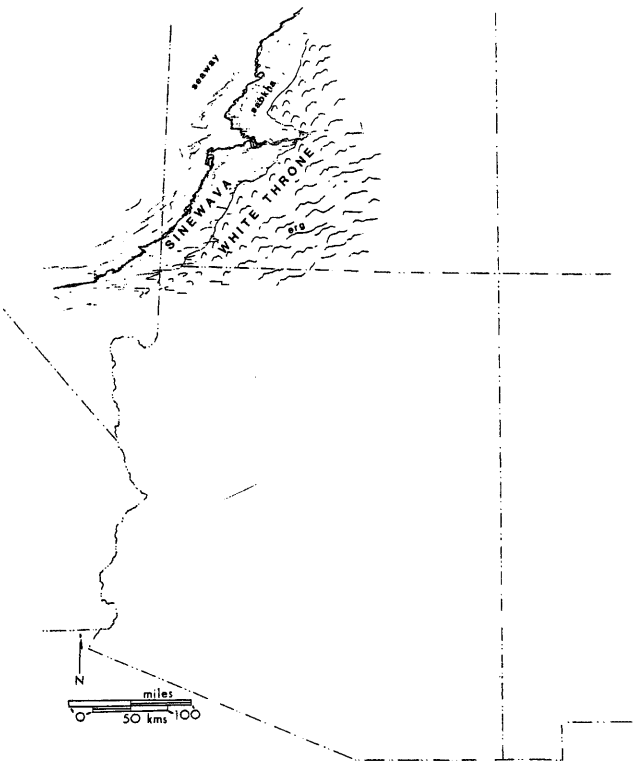

Figure 15. Hypothetical paleogeography during deposition of Temple Cap Sandstone.

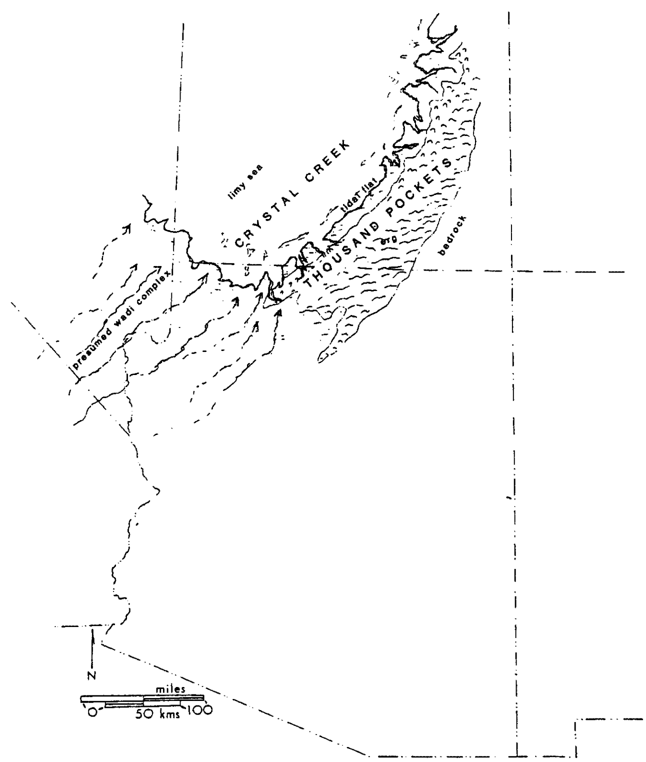

Figure 16. Hypothetical paleogeography during deposition of Page Sandstone and Judd Hollow Member of Carmel Formation (after Blakey and others, 1983).

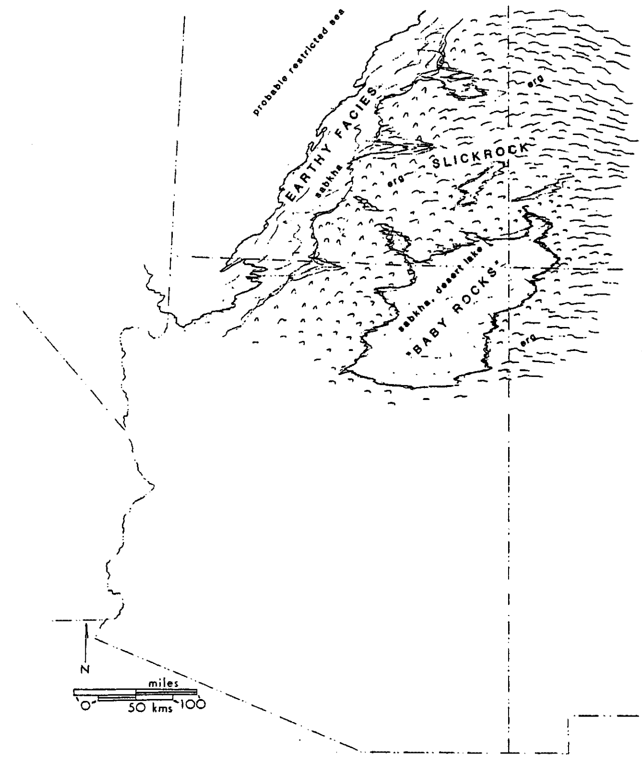

Figure 17. Hypothetical paleogeography during deposition of lower Entrada Sandstone (partly after Kocurek and Dott, 1983).

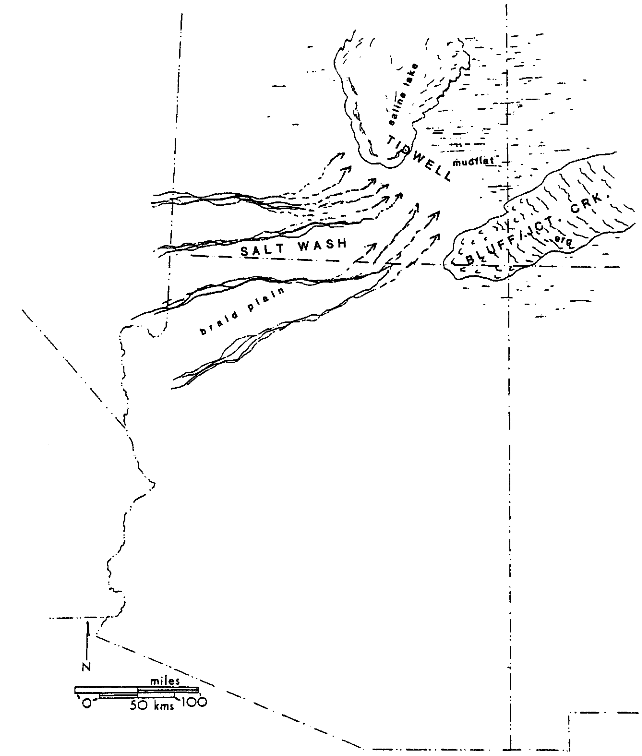

Figure 19. Hypothetical paleogeography during earliest deposition of Morrison Formation.

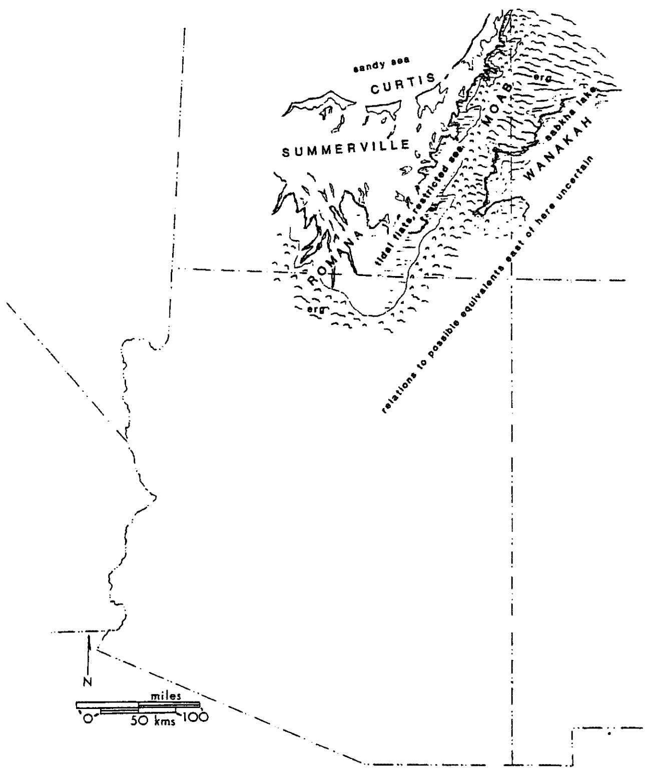

Figure 18. Hypothetical paleogeography during deposition of Summerville and Curtis Formations (partly after Kocurek and Dott, 1983).

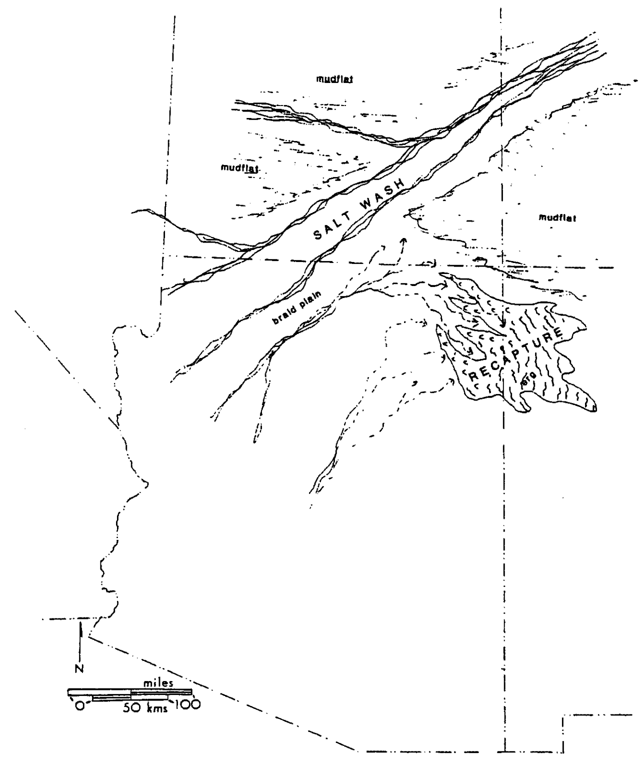

Figure 20. Hypothetical paleogeography slightly later than figure 19 during deposition of lower middle part of Salt Wash Member and equivalent part of Recapture Member of Morrison Formation.

Morrison Formation. Some of the field data gathered for this study was supported by grants funded by Organized Research, Northern Arizona University, Flagstaff. I was assisted with the drafting of figures by Teresa Mueller and Randy Hintz of Northern Arizona University. Pat Broyles and Barbara Ficker of the College of Arts and Science, NAU, typed the manuscript.

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