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Tectonic controls on deposition of Middle Jurassic strata in a retroarc foreland basin, Utah-Idaho trough, western interior, United States

Christian J. Bjerrum
Geological Institute, University of Copenhagen, Copenhagen, Denmark

Rebecca J. Dorsey
Department of Geology, Northern Arizona University, Flagstaff

Abstract. A thick succession of Jurassic nonmarine and marine sedimentary rocks is exposed in a large area from northern Arizona to eastern Idaho and western Wyoming. These sediments accumulated in the Utah-Idaho trough, a deep elongate cratonal basin whose origin has recently been debated. Detailed stratigraphic analysis, subsidence analysis, and first-order flexural modeling of these deposits (this study) provide new insights into the timing and mechanisms of subsidence in the Utah-Idaho trough. Lower and Middle Jurassic strata are divided into six unconformity-bounded sequences. In contrast to the overall uniform thickness of Lower Jurassic sequences (1 and 2), Middle Jurassic strata (sequences 3 through 6) consist of distinctly westward thickening sedimentary packages in which basal shallow marine deposits onlap eastward onto bounding unconformities. Basal strata of sequences 3 through 6 pass upward into widespread progradational continental deposits that are truncated progressively toward the east (cratonward) by the next unconformity. Decompacted total subsidence curves show that the rate of subsidence in most sections increased sharply at the end of sequence 2 time (J-2 unconformity; ~170 Ma). This is interpreted to record the onset of Middle Jurassic deposition in the distal part of a retroarc foreland basin. The unconformities and distinctive stratal geometries may have formed in response to forebulge migration caused by episodic thrusting in the Cordilleran orogen to the west. First-order flexural modeling was carried out to test the hypothesis of flexural subsidence in the Utah-Idaho trough. Trial-and-error comparisons produce a close match between decompacted stratigraphic profiles and model deflection profiles. The best fit is obtained using an infinite elastic plate ($D = 1 \times 10^{24}$ Nm), a moderate load topography, elevated base level, and an overfilled basin. Using recently published tectonic reconstructions for Nevada and Utah, we find close spatial agreement between a large Middle Jurassic fold-thrust belt and the supracrustal load inferred from model simulations. Our integrated basin analysis thus supports the interpretation of some previous studies that the Middle Jurassic Utah-Idaho trough was a retroarc foreland basin that formed east of a belt of regional contractile deformation and crustal thickening in western and central Nevada and southeastern California. Late Jurassic extension and normal faulting in northeastern Nevada may have been related to gravitational collapse of overthickened crust in the Cordilleran orogen. This coincides with a period of slowed subsidence in the Utah-Idaho trough that began at about 157 Ma.

Introduction

Jurassic sedimentary rocks are exposed in a large area of the western United States, from the Colorado Plateau of northern Arizona to southeastern Idaho and southwestern Wyoming (Figure 1). Systematic westward thickening of these sediments defines a deep Jurassic basin, the Utah-Idaho trough, which attains a thickness of more than 2000 m in west-central Utah [e.g., *Peterson*, 1986, 1988a]. The stratigraphy and sedimentology of these continental to shallow marine deposits are well known from numerous published studies [*Pipiringos and O'Sullivan,* 1978; *Peterson and Pipiringos,* 1979; *Imlay,* 1980]. To date, no regional quantitative basin analysis has been carried out on Middle Jurassic strata of the Colorado Plateau, largely because of limited age and stratigraphic data, difficulty in identification of lithostratigraphic marker beds and because the thick succession of strata in the western Utah-Idaho trough was removed by erosion at the regional sub-Cretaceous (K-1) unconformity [*Peterson,* 1988a]. Recent detailed studies have greatly improved our understanding of the stratigraphic and geologic development of the western Colorado Plateau region during Jurassic time [*Peterson*, 1988a, b; *Crabaugh and Kocurek,* 1993; *Riggs and Blakey,* 1993; *Blakey,* 1994; *Blakey et al.*, 1995]. Thus, it is now possible to carry out quantitative basin analysis using existing stratigraphic data to evaluate the regional tectonic processes that controlled Jurassic basin evolution in this region. To better understand the tectonic controls on basin development, it is helpful to compare results of quantitative basin analysis from cratonal strata in Arizona, Utah, and Wyoming (this study) with recent studies dealing with the tectonic evolution of the North American Cordillera to the west, in western Utah and Nevada.

Because early and middle Mesozoic tectonic events in the western Cordillera region have been strongly overprinted by later contractional and extensional events, interpretation of Middle Jurassic tectonics in the region remains controversial.

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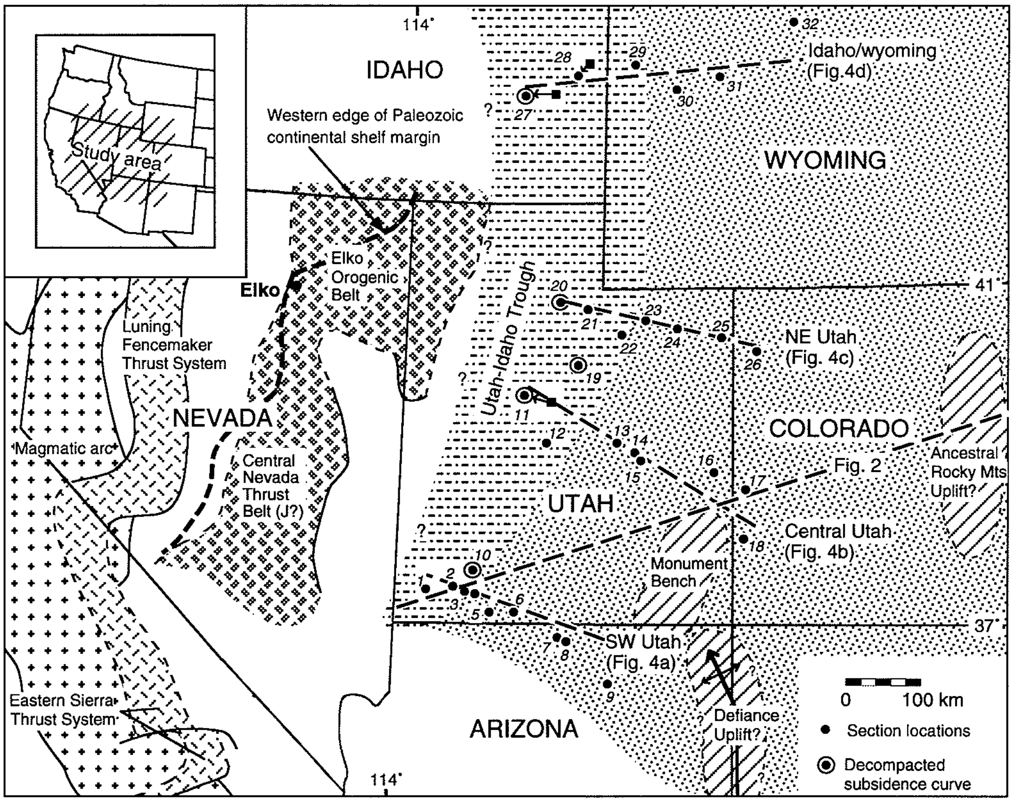

Figure 1. Map of western interior, United States, showing location of Lower and Middle Jurassic strata and probable Middle Jurassic orogenic rocks. Solid circles show location of sections used in basin analysis. Thin dashed lines represent stratigraphic cross section of Figure 2 and thickness profiles of Figure 4. Thick dashed line represents the western edge of Paleozoic continental shelf margin. Measured sections are from *Imlay* [1980]. Sections 11, 27, and 28 were palinspasticly restored using data from *Jordan* [1985]. Map is compiled from *Imlay* [1980], *Peterson* [1986, 1988a], *Camilleri et al.* [1992], *Smith et al.* [1993], and *Taylor et al.* [1993].

The Jurassic Utah-Idaho trough was thought by *Burchfiel and Davis* [1972] to be a retroarc foreland basin located east of an orogen and volcanic arc. Westward stratigraphic thickening and sedimentary petrology led *Jordan* [1985] to concur with this early interpretation. *Thorman et al.* [1992] also concluded that the Utah-Idaho trough developed as a foreland basin, based on overall basin geometry and probable late Middle Jurassic contractile deformation (Elko Orogeny) in the area of Elko, northeastern Nevada. A tectonic crustal load potentially responsible for the inferred foreland basin has recently been recognized in northeastern Nevada and northwestern Utah, where mapping and geobarometric data have been used to develop a model for Middle to Late Jurassic contractional deformation [*Camilleri et al.*, 1992; *Hodges et al.*, 1992]. The Middle to Late Jurassic Luning-Fencemaker thrust belt in western Nevada provides additional evidence for crustal loading during this time [*Oldow*, 1984; *Smith et al.*, 1993]. *Miller and Hoisch* [1992] showed that strong tectonic shortening and crustal thickening occurred along the sigmoidal bend in the Paleozoic continental shelf margin in NE Nevada (Figure 1). East and southeast of that area, it appears that only modest crustal thickening affected eastern Nevada, with localized crustal thinning and extension in western Utah late during this time [*Miller and Hoisch,* 1992]. In contrast with the above interpretations for regional contractile deformation, other studies have interpreted the Utah-Idaho trough to be a back arc rift basin controlled by regional extension and normal faulting [*Marzolf,* 1993, 1994a, b; *Moulton*, 1975; *Picha and Gibson,* 1985] or a basin controlled by dynamic topography as a result of viscous mantle flow [*Lawton*, 1994].

Today there is general agreement that western North America experienced a series of major Mesozoic contractile tectonic events that probably began in Middle Jurassic time (summarized by *Elison* [1991]), but the exact style and timing of arc/orogenic events remain controversial. The Jurassic volcanic arc and orogen was originally believed to be a high standing Andean-type arc [*Burchfiel and Davis,* 1972]. Later work questioned this interpretation for the southern part of the arc system and postulated a low-relief setting with transtensional intra-arc grabens similar to those found along the west coast of Central America today [*Busby-Spera*, 1988; *Busby-Spera et al.*, 1990]. New evidence from the Mojave Desert and the east Sierran thrust belt (Figure 1) contradicts this interpretation, at least for Middle Jurassic time, and instead indicates Middle Jurassic contraction in the Cordillera orogen [*Dunne and Walker*, 1993; *Boettcher and Walker*, 1993]. *Taylor et al.*

[1993] proposed that the central Nevada thrust belt may be linked to the late Middle Jurassic Elko Orogeny of *Thorman et al.* [1990] in NE Nevada. In an attempt to reconcile these conflicting models, some authors interpret the paleogeographic and tectonic setting for the Middle Jurassic western United States to be a continental magmatic arc that experienced local extension within the arc, coeval with contractional deformation in both forearc and backarc positions [*Dilek and Moores*, 1993; *Murchey and Blake*, 1993; *Smith et al.*, 1993]. *Schermer* [1993] proposed along-strike variations in structural style to explain these apparent discrepancies, suggesting that regional deformation during Middle Jurassic time varied from dominantly contractile strain in the north (Sierra Nevada to the Mojave Desert) to dominantly arc-related extension in the south (Sonoran Desert). These problems remain unresolved.

We believe Middle Jurassic tectonic events in Nevada should be reflected in sedimentary deposits of the nearby, age-equivalent Utah-Idaho trough. Often it is possible to infer the timing and processes of subsidence in thick synorogenic basins based on the distribution of lithofacies, geometries of stratal packages, and rates of subsidence and sediment accumulation [*Jordan et al.*, 1988; *Angevine et al.*, 1990; *Sinclair et al.*, 1991]. Furthermore, the timing of regional tectonic events is often more precisely recorded in the stratigraphy of flanking synorogenic basins than in rocks of the orogen that controlled those events.

In this paper we present the results of regional basin analysis and first-order flexural modeling of Middle Jurassic sedimentary rocks of the Utah-Idaho trough, which are now exposed in the central and western parts of the Colorado Plateau (Figure 1). Interpretation of the tectonic origin of the Middle Jurassic Utah-Idaho trough is made difficult by the following problems: (1) strata deposited in the central and western parts of the Utah-Idaho trough have been removed by erosion at the K-1 unconformity; (2) a large percentage of Middle Jurassic strata are continental and have limited age resolution; (3) deformed rocks to the west in Nevada have experienced multiple phases of deformation and metamorphism, resulting in widely divergent views on the tectonic evolution of the Middle Jurassic Cordillera. In spite of these limitations, the regional basin analysis presented in this paper provides useful insights into the tectonic origin of the Middle Jurassic Utah-Idaho trough. This analysis, which utilizes data from existing publications, lends support to earlier inferences that the Utah-Idaho trough was a large retroarc foreland basin that formed in response to regional-scale crustal loading in the Cordillera orogen to the west, in Nevada and SE California. In addition, this study and the data compiled herein should help improve the previously established link between known stratigraphy of the Colorado Plateau and deformed metamorphic rocks to the west in the Great Basin.

Regional Stratigraphy

Riggs and Blakey [1993] informally defined six unconformity-bounded, composite sequences [*Mitchum and Van Wagoner*, 1991] in Jurassic strata of the southern Colorado Plateau. Using published regional biostratigraphic and lithostratigraphic correlations [*Imlay*, 1980; *Peterson*, 1988a, b; *Blakey et al.*, 1995], we have applied these stratigraphic subdivisions and informal nomenclature to a larger region, which includes parts of Arizona, Utah, Colorado, Idaho, and Wyoming (Figures 1 and 2). Stratigraphic thicknesses and biostratigraphic data used in this study are largely from *Imlay* [1980] (see Table 1[1]); approximate absolute age assignments of formations and sequence boundaries are based on the timescale of *Harland et al.* [1989]. Our knowledge of the stratigraphy stems mainly from the southern part of the study area. For that area we give a brief description of each sequence, its bounding unconformities, and general sedimentologic interpretations, as outlined by *Riggs and Blakey* [1993] and *Blakey et al.* [1995]. The depositional environments for the nothern part of the study area (northern Utah and Idaho/Wyoming) differ slightly from the southern area. However, because widespread Jurassic unconfomities can be traced all over the region [*Pipiringos and O'Sullivan*, 1978], tectonic interpretations based on facies architecture in the southern area can be extrapolated with resonable confidence to the north.

Sequences 1 and 2 (Glen Canyon Group) overlie the extensive J-0 unconformity (Figures 2 and 3). These two sequences are separated by another disconformity (J-sub Kay) and are here treated together (Sequence 1/2). Sequence 1/2 consists of sabkha, fluvial, and eolian deposits of Early Jurassic age [*Litwin*, 1986; *Imlay*, 1980]. *Marzolf* [1983] proposed that the depositional environments of sequence 2 are time-transgressive from east to west (Figure 3). The fluvial deposits show a paleotransport direction from the craton and obliquely perpendicular to the basin axis toward the west and north-west (Figure 3). Sequence 1/2 is truncated by the J-1 and J-2 unconformities. *Pipiringos and O'Sullivan* [1978] estimated that the J-1 formed over a period of approximately 2-3 million years. Estimates of the amount of erosion associated with the J-1 unconformity are difficult because of the limited understanding of the chronostratigraphic relationships in the Navajo Sandstone [*Blakey*, 1994].

The areally restricted sequence 3 consists of the Temple Cap Sandstone, the Gypsum Spring Member of the Twin Creek Limestone, and the Gypsum Spring Formation (Figures 2 and 3). This sequence overlies the J-1 unconformity and consists of basal transgressive deposits overlain by regressive deposits that pinch out or are eroded toward the east. In Idaho, a western and southern source area is indicated by increased amount of sand toward the west [*Imlay*, 1967]. The sequence is probably of late Aalenian?/early Bajocian age [*Imlay*, 1980]. The J-2 unconformity truncates sequence 3 and progressively older deposits toward the east (Figure 3). The J-2 unconformity has been estimated to have formed over a period of about 1 million years [*Pipiringos and O'Sullivan*, 1978]. The amount of erosion associated with the J-2 unconformity is dif-

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[1] An electronic supplement of this material may be obtained on a diskette or Anonymous FTP from KOSMOS.AGU.ORG. (LOGIN to AGU's FTP account using ANONYMOUS as the username and GUEST as the password. Go to the right directory by typing CD APEND. Type LS to see what files are available. Type GET and the name of the file to get it. Finally, type EXIT to leave the system.) (Paper 95TC01448, Tectonic controls on deposition of Middle Jurassic strata in a retroarc foreland basin, Utah-Idaho trough, western interior, United States, Christian J. Bjerrum and Rebecca J. Dorsey). Diskette may be ordered from American Geophysical Union, 2000 Florida Avenue, N. W., Washington, DC 20009; $15.00. Payment must accompany order.

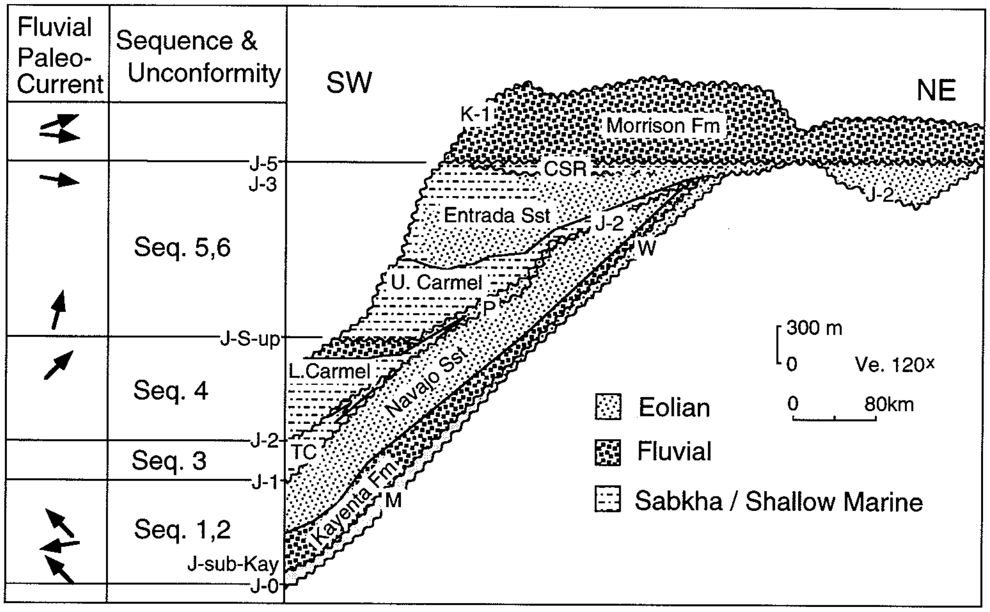


Figure 2. Simplified stratigraphic cross section of Jurassic rocks from southwestern Utah to central Colorado, showing the six sequences and bounding unconformities used in this study (modified from *Peterson* [1988a] and *Pipiringos and O'Sullivan* [1978]). Abbreviations are M, Moenave Formation; W, Wingate Sandstone; TC, Temple Cap Sandstone; P, Page Sandstone; CSR, Curtis and Summerville Formations and Romana Sandstone. Fluvial paleocurrents are from *Riggs and Blakey* [1993].

ficult to assess, but possibly 100-300 m of strata were eroded judging from the short distance over which sequence 1 is truncated [*Blakey*, 1994].

Sequence 4 consists of the lower Carmel Formation, Page Sandstone, and equivalent Sliderock Member to Boundary Ridge Member of the Twin Creek Limestone, middle Arapian Shale, and lower Sundance Formation (Figures 2 and 3). The basal part of sequence 4 is made up of transgressive deposits, defining a transgressive systems tract, which exhibit progressive shallow-marine onlap toward the east onto the J-2 uncon-

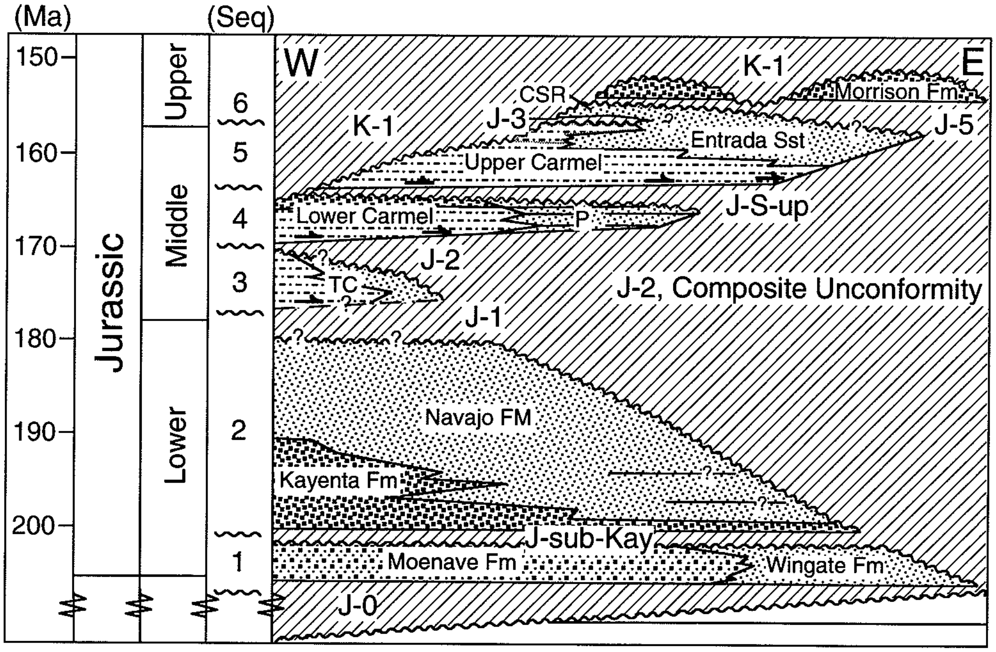


Figure 3. Chronostratigraphic diagram of Figure 2. Compiled from *Blakey et al.* [1995], *Everett et al.* [1989], *Imlay* [1980], *Litwin* [1986], *Marzolf* [1983], *Peterson* [1988a], *Pipiringos and O'Sullivan* [1978], and *Riggs and Blakey* [1993].

formity [*Blakey et al.*, 1995; *Riggs and Blakey*, 1993]. Small pebbles in the western part of the Sliderock Member (lower sequence 4) indicate derivation from a western source [*Imlay*, 1980]. The lowermost strata of sequence 4 are of middle Bajocian age [*Imlay*, 1967, 1980] and have been dated to approximately 169.5 Ma (Ar/Ar on biotite and sanidine from bentonites) [*Everett et al.*, 1989]. Younger strata of sequence 4 (upper part of the Limestone Member of the Carmel Formation, Page Sandstone, Sliderock Member, and Rich Member of the Twin Creek Limestone) consist of interfingering eolian deposits and shallow marine/coastal deposits that comprise a high-stand systems tract (Figures 2 and 3) [*Blakey et al.*, 1995; *Havholm et al.*, 1993]. In the southern part of the Utah-Idaho trough, the upper part of sequence 4 comprises a shelf-margin systems tract of sabkha and fluvial deposits with paleocurrents directed toward the east and northeast, obliquely across the basin axis [*Riggs and Blakey*, 1993]. Fluvial deposits interfinger with and pass laterally into eolian deposits in the east and southeast (Figures 2 and 3). During deposition of sequence 4, the basin was flanked by a broad uplift or area of less subsidence on the east (the Monument bench) and the Defiance uplift on the southeast (Figure 1) [*Peterson*, 1986]. The J-S-up unconformity progressively truncates eolian super bounding surfaces of sequence 4 toward the east and northeast and eventually merges with the J-2 unconformity (Figure 3) [*Blakey et al.*, 1995; *Havholm et al.*, 1993]. Within the available Jurassic age resolution, super bounding surfaces can be considered to be time lines [*Kocurek and Havholm*, 1993]. In the northern part of the Utah-Idaho trough regressive marine deposits are capped directly by the J-S-up unconformity. The J-S-up unconformity is estimated to have formed over a very short period [*Riggs and Blakey*, 1993] and removed approximately 70 m of strata toward the northeast.

Sequence 5 consists of the upper Carmel Formation, upper Twin Creek Limestone, upper Arapian Shale, Entrada Sandstone, Preuss Sandstone and middle Sundance formation (Figures 2 and 3). Similar to sequences 3 and 4, it is characterized by initial eastward shallow-marine onlap onto its basal disconformity and unconformity (J-S-up unconformity; *Blakey et al.* [1995]). In southern Idaho and southwestern Wyoming, the lower part of sequence 5 shows transgressive onlap eastward over truncated strata of sequence 3 [*Imlay*, 1967]. This transgressive depositional pattern was followed by expanding continental eolian deposits and a final transgression [*Crabaugh and Kocurek*, 1993; *Peterson*, 1988a, b]. More sands and eventually pebbles in the western part of sequence 5 record eastward progradation of clastic units from the west through time [*Imlay*, 1967]. The Monument bench continued to be a structural high through sequence 5 time [*Peterson*, 1986].

Sequence 5 is truncated by the minor J-3 unconformity (Figure 3). The J-3 unconformity is a ravinement surface formed as a result of a partial marine transgression of the eolian Entrada sand sea from the northwest, and it is probably not as significant as the other Jurassic unconformities (G. Kocurek, personal communication, 1994). Sequences 5 and 6 are therefore treated together in the following analysis. Sequence 6 consists of the Curtis Formation, Summerville Formation, Stump Formation, and the Romana Sandstone. Sequence 6 is characterized by basal transgressive deposits that are overlain by regressive marine deposits, all of which probably are progressively truncated toward the east by the J-5 unconformity. The youngest part of sequence 6 (Summerville/Romana Sandstone) in the southern part of the study area contains fluvial deposits with paleocurrents directed perpendicular to the basin axis toward the east [*Riggs and Blakey*, 1993]. In the north, the J-5 unconformity caps regressive marine deposits. The J-5 unconformity was estimated by *Pipiringos and O'Sullivan* [1978] to have formed over a period of less than 2 m.y. The amount of erosion associated with the J-5 unconformity is uncertain.

During Late Jurassic time, detrital sediments of the Morrison Formation were derived from an uplifted eroding orogenic belt to the west and deposited in an ancient fluvial system that flowed toward the ancestral Gulf of Mexico [*Thorman et al.*, 1992].

All Middle Jurassic sequences are truncated sharply toward the west by the sub-Cretaceous, K-1 unconformity (Figure 2) [*Peterson*, 1988a]. It appears that a large volume of strata from the proximal (western) and central part of the Utah-Idaho trough were removed by erosion sometime between Late Jurassic and late Early Cretaceous time. Stratigraphic analysis combined with numerical basin modeling of Lower Cretaceous gravels in the western interior has shown that this episode of erosion is probably best explained by a regional thermal uplift that was related to Late Jurassic-Early Cretaceous arc magmatism in the western United States [*Heller and Paola*, 1989].

Unconformities

The geometry and age relations of erosional unconformities vary significantly from Lower to Middle Jurassic strata, as shown in Figure 3. The J-0 unconformity cuts down section from the Four Corners area toward the west and southwest, ultimately eroding into Paleozoic rocks in the Mojave Desert, SE California [*Marzolf*, 1991]. In contrast, the J-2, J-S-up, J-5, and possibly the J-1 unconformities cut down toward the east and northeast [*Pipiringos and O'Sullivan*, 1978; *Blakey et al.*, 1995]. The J-2 and J-S-up are disconformities in the west [*Peterson and Pipiringos*, 1979; *Blakey et al.*, 1995] and become angular unconformities toward the east as they cut progressively down section in the Navajo/Wingate and Page Sandstone, respectively [*Havholm et al.*, 1993; *Blakey*, 1994]. Erosion on the J-2 and J-S-up unconformities is estimated to have removed approximately 100 to 300 m and 70 m of section, respectively, in the east and less than this toward the west. In southeastern Utah and northern Arizona, we estimate that the J-2 unconformity represents 10 to 30 m.y. (Figure 3). In this area the J-2 unconformity is a great hiatus that we interpret as being composite and formed by several periods of erosion and nondeposition. We tentatively interpret the eastward merging of the J-1 and J-2 unconformities to indicate that erosion which formed the composite erosional unconformity ("J-2") in the east started as early as J-1 time. The J-5 unconformity truncates strata of sequence 6 and underlying unconformities (J-3 and J-2) [*Pipiringos and O'Sullivan*, 1978; *Peterson*, 1988a, b] and thus probably cuts down section toward the east (Figure 2 and 3).

Sequence Thickness Trends

Figure 4 presents four west-east stratigraphic thickness profiles for sequences 1/2, 3, 4, and 5/6, from southern Utah to southeastern Idaho and western Wyoming. These plots show regional variations in decompacted thickness, calculated for the time when the top of each sequence was at the surface. The profiles were constructed by removing the Cretaceous and Tertiary overburden [*Hintze*, 1988] and progressively decompacting the stratigraphic sections of *Imaly* [1980], *Peterson and Pipiringos* [1979], and *Peterson* [1988a], using the method of *Sclater and Christie* [1980]. Porosity values were assigned according to the average lithology of each member in a sequence. Because most of the sequences were deposited in shallow water (<50 m), paleobathymetry was not included in construction of the profiles. Only a minor amount of evaporites were present in the sections used, so preferential structural thickening of evaporites is not a concern in the stratigraphic analysis.

The profiles in Figure 4 show an overall trend of thickening toward the west, with important variations between sequences. The geometry of sequence 1/2 differs significantly from that of sequences 3, 4, and 5/6. These variations are discussed below.

Qualitative Basin Analysis

Regional Tectono-stratigraphic Interpretation

The direction of downcutting on major unconformities is important because it provides information about the geometry and possible origin of regional tilting episodes that produced the unconformities. Westward downcutting on the J-0 unconformity requires tilting toward the east and associated erosion of progressively older strata to the west [*Marzolf*, 1991]. *Marzolf* [1991] suggested that this regional-scale eastward tilting could have resulted from thermal doming during initiation of the Cordillera magmatic arc and/or onset of related contractile deformation in a fold-thrust belt. Broad, uniform post-J-0 subsidence across the basin, with a increase in the southwestern part of the Colorado Plateau, is suggested by thickness profiles (Figure 4) and isopach trends [*Peterson*, 1986]. The subsidence pattern of sequence 2 is poorly understood because of the lack of marker beds in the thick eolian succession [*Blakey*, 1994]. Based on subsidence analysis and stratigraphic analysis in southern Utah, *Verlander* [1994] proposed that sequence 2 was deposited in a broad asymmetric basin that was controlled in part by dynamic topography

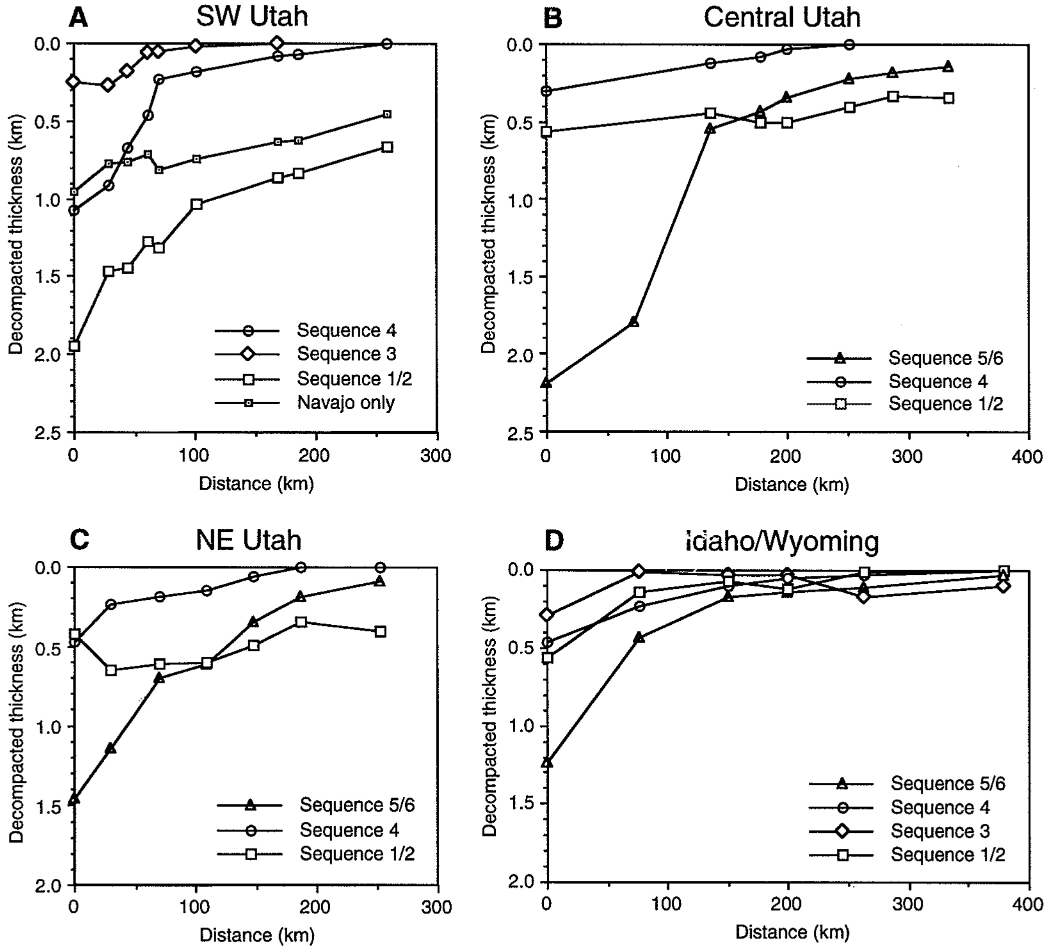


Figure 4. Decompacted W-E thickness profiles of sequences from SW Utah to Idaho/Wyoming. Each plot shows the pronounced westward thickening of the Middle Jurassic sequences 4 and 5/6 and only limited thickening of the Lower Jurassic sequence 1/2. Location of cross sections is shown in Figure 1. See text for details.

resulting from viscous mantle convection [*Gurnis*, 1992] and in part by flexural response to thrust loading southwest of the Colorado Plateau.

Data from Middle Jurassic strata indicate that a major change in basin configuration occurred around J-2 time (169.5 Ma) [*Peterson*, 1986]. The J-2 unconformity records regional scale westward tilting of the crust and a marked narrowing of the basin that continued through Middle Jurassic time (Figures 3 and 4). We suggest that this change may have occurred as early as J-1 time (~175 Ma), because the J-2 probably is a composite unconformity east of the sequence 3 pinch-out. In southwestern Utah, decompacted thickness profiles indicate a change from very broad, uniform to slightly asymmetric subsidence during sequence 1/2 time to a period of pronounced westward asymmetric subsidence beginning at least by the time of sequence 4 deposition (Figure 4a). East and northeast directed paleocurrents recorded in the upper parts of sequences 4 and 5/6 in the southern Utah-Idaho trough indicate that alluvial sediments prograded across the basin to the east where they pass laterally into eolian strata [*Riggs and Blakey*, 1993; *Blakey*, 1994]. Around the time of J-3 erosion, asymmetrical subsidence toward the west decreased, and eventually by J-5 time a more uniform pattern of regional subsidence was established [*Peterson*, 1986].

Middle Jurassic Basin Formation

We have considered three major basin-forming mechanisms that could have caused the onset of regional westward tilting and asymmetric subsidence, as recorded in strata above the J-1 unconformity: (1) crustal thinning in a continental rift basin [*Moulton*, 1975; *Picha and Gibson*, 1985; *Marzolf*, 1993, 1994a, b]; (2) dynamic topography created by viscous mantle flow associated with a newly established subduction zone [*Lawton*, 1994; *Gurnis* 1992]; and (3) flexural subsidence in a retroarc foreland basin [*Burchfiel and Davis*, 1972; *Jordan*, 1985; *Heller et al.*, 1986; *Thorman et al.*, 1990, 1992]. Other mechanisms such as thermal contraction and development of a passive margin-type "steershead" geometry [*Watts et al.*, 1982] would not be expected to produce the observed depth and large scale of subsidence represented in these strata. A back arc rift-basin interpretation appears unlikely based on the regular, systematic westward thickening seen in Middle Jurassic strata (Figure 4), which is unlike irregular profiles commonly seen in rift basins. Basin subsidence as a result of dynamic topography seems unlikely because of the large cumulative thickness of middle Jurassic strata and the large distance of the basin from the convergent-margin subduction zone, compared to stratigraphic models of *Gurnis* [1992]. We therefore believe that Middle Jurassic subsidence and sedimentation in the Utah-Idaho trough probably resulted from regional-scale flexural depression of the lithosphere in a large foreland basin, in response to crustal loading in the Cordilleran orogen to the west.

Foreland-Basin Stratigraphic Model

The stratigraphic geometries and depositional patterns of sequences 3, 4, and 5/6 (Figures 2 - 4) bear strong resemblance to those of well-documented retroarc foreland basins such as the north Alpine foreland basin [*Sinclair et al.*, 1991] and the Cretaceous Alberta foreland basin [*Plint et al.*, 1993], as well as recent numerical models for foreland basins [*Jordan and Flemings*, 1991], in the following ways. First, Middle Jurassic unconformities are disconformities near the paleobasin center (in the west) and become angular unconformities toward the craton (east). Second, erosional vacuities probably increase in duration toward the craton; evidence for this consists of erosional unconformities that cut into progressively older deposits toward the east and the observation that each sequence onlaps eastward onto each underlying unconformity. Third, each sequence is characterized by basal transgressive marine deposits that are progradationally overlain by continental deposits. Alluvial deposits in the southern part of the Utah-Idaho trough contain fluvial paleocurrents that are directed obliquely across the basin axis toward the east and northeast [*Riggs and Blakey*, 1993], indicating that the basin became overfilled during basin-filling and progradational episodes. Fourth, each sequence displays distinctive systematic thickening toward the west, toward a known orogenic belt that probably was active during Jurassic time, although the exact timing of regional contractile deformation remains poorly constrained.

Stratigraphic, depositional, and temporal patterns seen in Middle Jurassic strata are strikingly similar to synthetic stratigraphy produced in numerical models of foreland basins in which subsidence is controlled by episodic thrusting in the fold-thrust belt [*Heller et al.*, 1988; *Flemings and Jordan*, 1990; *Jordan and Flemings*, 1991]. In these models, unconformities form in the distal part of the basin (toward the craton) during periods of active thrusting, when deep flexural subsidence is located close to the thrust belt and uplift occurs in the area of the outer flexural bulge (Figure 5a). During periods of tectonic quiescence, the thrust belt experiences erosion and isostatic rebound, which reduces accommodation space in the proximal part of the basin and causes the load to be redistributed into the basin via sediment transport and deposition (Figure 5b). This produces sedimentation over a much larger area in an overfilled basin, and coarse-grained clastic sediments prograde out over fine-grained deposits of the active-thrusting phase (Figures 5b and d). The hiatus associated with the unconformities increases in duration toward the craton (Figure 5d). Initial marine onlap of sediments onto the forebulge takes place during the active thrusting phase, followed by regression (quiescent phase) in which continental sediments may prograde across the entire width of the basin if sediment input is large or base level is low [*Jordan and Flemings*, 1991]. Unconformity-bounded stratigraphic packages in the models show pronounced thickening of basin-filling deposits toward the orogen. The period of erosion or nondeposition associated with forebulge migration is greatest in the central part of the basin (at 125 km, Figure 5d) and in the distal most part of the basin. If the model had been run with lower base level, the forebulge unconformity would probably be continuous from ~125 km to the craton in the east.

We propose that Middle Jurassic unconformities (J-1, J-2, J-S-up, and J-5) may have formed by migration of an outer flexural bulge in response to episodic thrusting in the Cordilleran fold-thrust belt to the west. We favor episodic thrusting instead of steady load propagation with superimposed sea-level fall, because of the large regional extent of the observed unconformities [*Jordan and Flemings*, 1991]. This is, however, a tentative interpretation, since it is now clear that other lithospheric processes such as variations in intraplate stress [*Cloetingh*, 1988; *Heller et al.*, 1993], viscoelastic relaxation of the lithosphere [*Beaumont*, 1981], and sea-level fall, all can exert a strong control on vertical crustal movements and development of unconformities in continental foreland basins.

The proposed global Aalenian and Middle Jurassic eustatic lowstand and subsequent long-term rise in sea level [*Haq et al.*, 1988] have been shown to be a local North Sea phenomenon produced by thermal doming [*Underhill and Partington*, 1993]. The long-term sea-level low and rise are therefore not considered to have had any primary effect on the development of the Middle Jurassic unconformities and strata of the Colorado Plateau. Furthermore, a fall in eustatic sea level alone would not produce the basin-wide tectonic tilt that is associated with unconformities in Middle Jurassic strata of the Colorado Plateau region.

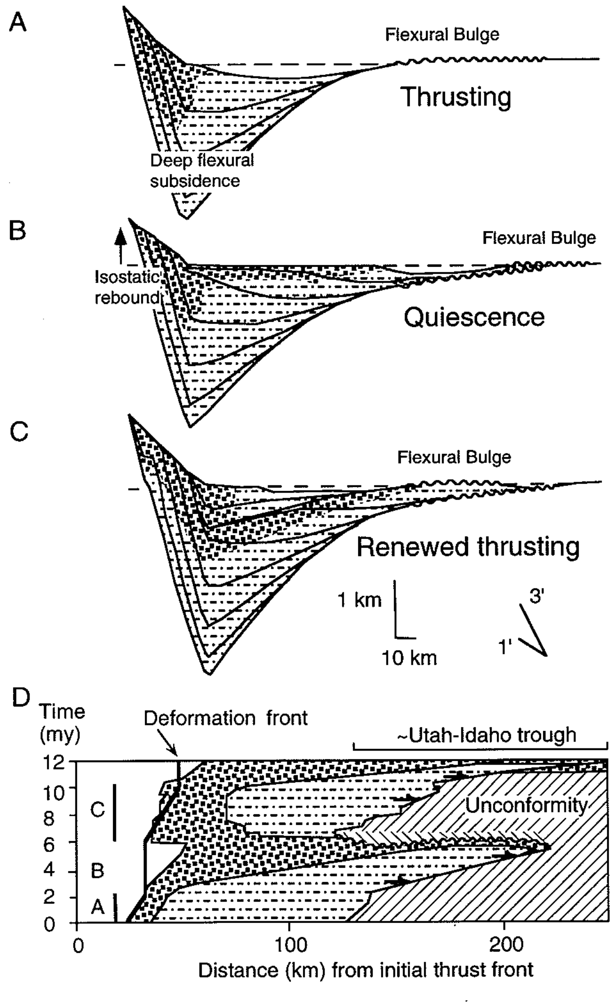


Figure 5. Foreland-basin stratigraphic model, tectonically controlled by episodic thrusting in the orogen to the (left) west (modified from *Jordan and Flemings* [1991]). (a-c) Sequential steps of thrust cycles. Note migration of flexural bulge and associated erosion that form unconformities. (d) Chronostratigraphic diagram resulting from foreland-basin model. Area corresponding to the Middle Jurassic stratigraphy indicated. Patterns as in Figure 2.

Subsidence Analysis

Five stratigraphic sections were chosen for subsidence analysis, based on their relatively large thickness and their position as close to the paleo-basin axis as the preserved stratigraphy permits (Figure 6). The sections were constructed using thickness data from Imlay [1967, 1980] and age assignments from *Everett et al.* [1989], *Imlay* [1980], and *Litwin* [1986]. The stratigraphic sections were decompacted using the first step of *Sclater and Christie* [1980], where also Cretaceous and Tertiary overburden was included in the calculations. Total subsidence curves were then constructed for each of these five sections with the Jurassic interval shown in Figure 7. Back stripping to remove the effects of the sediment load and construct a tectonic subsidence curve was not carried out, as it is inaccurate to assume Airy isostatic response to sediment loading in foreland basins [*Jordan et al.*, 1988].

In constructing the subsidence curves, we assumed that early cementation did not take place in clastic deposits. In carbonate rocks, however, early cementation during burial is common and can greatly reduce the amount of compaction in the sediment [*Bond and Kominz*, 1984]. Vertical error bars in Figure 7a represent the range of possible thicknesses, depending on whether or not early cementation occurred in carbonate units. Because most sequences probably were deposited at very shallow water depths (<50 m), no variations in paleobathymetry were included in the curves (Figure 7). Absolute ages of Jurassic formations are not well constrained. Most of the absolute ages were estimated by conversion from biostratigraphic age data [Imlay, 1980] and have been assigned an uncertainty of ± 2 m.y. Sequence 1 and part of sequence 2 have been assigned Sinemurian to Pliensbachian ages based on palynomorphs [*Litwin*, 1986]. The upper part of sequence 2 and all of sequence 3 have been assigned Toacian to early Bajocian age, respectively, based on their stratigraphic position [*Imlay*, 1980]. The lower part of sequence 4 has been dated as middle Bajocian based on the presence of scarce ammonites [*Imlay*, 1980] and absolute Ar/Ar dates on bentonites [*Everett et al.*, 1989]. A Bathonian age of the upper part of sequence 4 and the basal part of sequence 5 is based on the stratigraphic position between the dated lower part of sequence 4 and the ammonite-dated early Callovian strata of the last part of sequence 5 in northern Utah [*Imlay*, 1980]. Future age dating of numerous bentonites will likely change the detailed shape of the subsidence curves, but we expect that their overall forms will remain the same.

Although absolute rates of Jurassic subsidence are not well constrained due to uncertainties in age data, the subsidence curves reveal quite clearly the overall patterns and changing relative rates of subsidence through time (Figure 7). The curves are difficult to interpret for Early Jurassic time because they differ considerably between different locations and because of uncertainties in palynostratigraphic age assignments of *Litwin* [1986]. Until absolute age dates are obtained from key Lower Jurassic rocks, the major basin-forming mechanism for sequence 1/2 time will remain uncertain and debatable. In

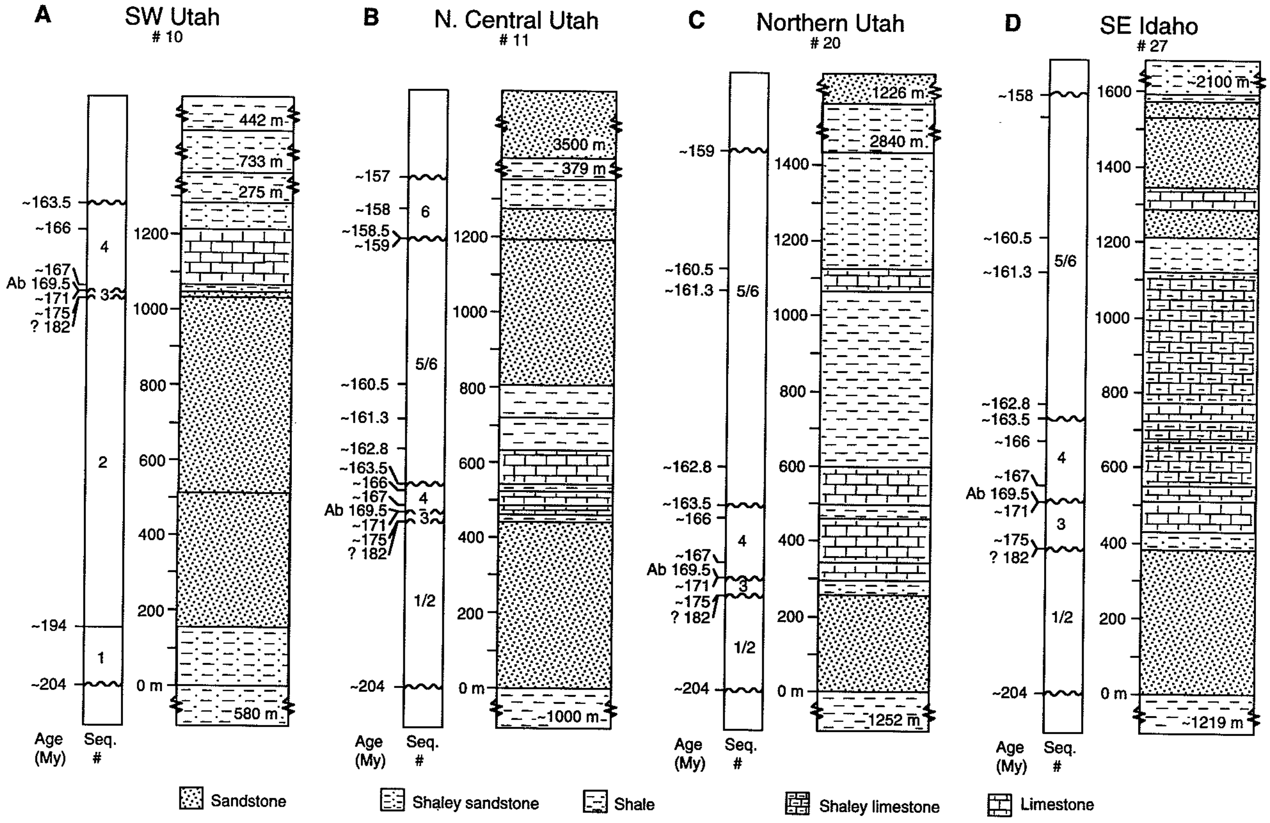


Figure 6. Stratigraphic sections used for subsidence analysis, from *Imlay* [1980], showing the assigned lithology types and age dates. Ab is absolute date (Ar/Ar, zircons from bentonites, *Everett et al.* [1989]); ~ is approximate conversion from biostratigraphic ages [*Imlay*, 1980; *Litwin*, 1986]. Underlying Triassic and overlying Jurassic Morrison Formation, Cretaceous and Tertiary rocks are shown as compressed intervals. Section 19 is not shown because it is similar to section 11. Location of sections is shown in Figure 1.

middle Bajocian time (~ 169 Ma, asterisk on Figures 7a and 7b), the basin experienced a pronounced acceleration in total subsidence rate, from ~0.02 - 0.06 km/m.y. to ~0.1 - 0.5 km/m.y. A similar Bajocian increase in subsidence rate was documented by *Heller et al.* [1986] in western Wyoming, using the biostratigraphic age assignments of *Imlay* [1980]. This acceleration was attributed by them to a tectonic event that probably took place west of the Sevier thrust belt. Farther north, in southern Alberta, Canada, another similar acceleration in subsidence was documented for middle Bajocian time [*Kominz and Bond*, 1986]; in that study ages were determined from ammonite biostratigraphy [*McCrossan and Glaister*, 1964]. *Kominz and Bond* [1986] interpreted the convex-up inflection in subsidence to record onset of flexural subsidence in the Alberta basin, a well-documented foreland basin. The very close timing of regional acceleration of basin subsidence, in a belt extending from central Utah [this study] to western Wyoming [*Heller et al.*, 1986; this study] to southern Alberta [*Kominz and Bond*, 1986], suggests that the basins experienced a similar large-scale regional control on basin subsidence. This is best attributed to onset of flexural subsidence in one or a series of related foreland basins during Bajocian time, in response to a major episode of thrust-induced crustal loading in the Canadian and United States Cordilleran orogenic belt to the west [*Kominz and Bond*, 1986; *Jordan*, 1985]. Relatively rapid flexural subsidence persisted through deposition of sequence 5/6, until about 157 Ma (Figure 7). During deposition of the Late Jurassic Morrison Formation (Figure 7), total subsidence rates slowed to 0.03 - 0.06 km/m.y. *Thorman et al.* [1992] also attributed the relatively uniform thickness of the Morrison Formation to a cessation of the orogenic contractional deformation corresponding to a associated decrease in subsidence rate.

Flexural Modeling

Modeling Strategy

In this section, we present a simple test of the hypothesis that flexural subsidence in the Utah-Idaho trough resulted from tectonic loading by the Cordilleran orogen to the west. To calculate flexural subsidence due to crustal loading, we assume that the lithosphere responds to vertical loads as an elastic plate overlying an inviscid fluid layer [*Turcotte and Schubert*, 1982]. The modeling approach follows that of numerous other studies [*Jordan*, 1981; *Nunn et al.*, 1987], in which model results are compared with observed stratigraphic profiles in foreland basins to help determine the physical properties of underlying lithosphere and the distribution of topographic and subsurface loads in nearby mountain ranges. Deflections were calculated using a five-point finite-difference approximation [*Abramowitz and Stegun*, 1972] to the two-dimensional elastic flexure equation. The finite-difference approximation has been successfully tested by comparing deflections calculated for a rectangular load distribution with analytical solutions [*Angevine et al.*, 1990]. Similar numerical schemes to solve the elastic deflection equation were used by *Madsen et al.* [1984].

Figures 8a and 8b show the effects of varying flexural rigidity (D) and size of the topographic load, assuming an infinite elastic plate. For this study we used two model topographic profiles ("medium" and "large", Figure 8c), chosen because they represent a likely range of values for mountain-belt topography in western to central Nevada and southeastern California during Middle Jurassic time. The width of the mountain-belt load is estimated from palinspastically restored Middle Jurassic paleogeography [*Saleeby et al.*, 1992]. Because structural and stratigraphic data in Nevada and Utah are insufficient to permit reconstruction of Middle Jurassic thrust loads, we used the restored elevation of the Sevier thrust belt [*Jordan*, 1981] as a reasonable approximation of elevation in the Jurassic orogen. Although the Jurassic and Cretaceous fold-thrust belts formed in different positions at different times, the conditions of metamorphism at depth (greenschist to amphibolite grade), and hence crustal thickening, appear to have been similar [e.g., *Oldow*, 1984, 1993; *Smith et al.*, 1993; *Dilek and Moores*, 1993]. While this is only an approximation, it helps us choose reasonable ranges of model topography for the Jurassic fold-thrust belt in Nevada. In the flexural models, sediment is allowed to iteratively fill each deflection, so that all sediment filling the basin is included in the total calculated load. Densities of 2750 kg/m^3 and 2250 kg/m^3 were used for mountain-belt and sediment loads, respectively. For modeling purposes, we have treated sequences 4 and 5/6 separately.

Flexural models used in this study do not include erosion in the mountain belt or sediment transport in the basin, both of which have been simulated as diffusion-controlled processes in other recent studies [*Flemings and Jordan*, 1990; *Jordan and Flemings*, 1991; *Sinclair et al.*, 1991]. The effects of thermal anomalies and resulting buoyancy forces [*Kominz and Bond*, 1986] also have not been included in the model. We have chosen a simpler modeling strategy because we seek to answer a simple question: is the geometry of stratigraphic profiles in the Utah-Idaho trough (Figure 4) compatible with a flexural mechanism of basin formation? While the quality of stratigraphic data is adequate for addressing this basic question, we feel that more and better-quality age data would be required to attempt more complex, time-dependent modeling of basin subsidence and diffusional erosion and sedimentation.

In our initial flexural modeling experiments, sediment was allowed to fill the flexural deflection to the zero datum (Figures 4 and 9). These models consistently produced flexural profiles that were narrower and steeper than the stratigraphic thickness profiles (Figure 9) and therefore seemed unsatisfactory for reasonable flexural rigidities (5.0 x 10^{23} to 1.0 x 10^{24} Nm). Based on fluvial paleotransport toward the east and northeast and the observation that fluvial sediments interfinger with eolian sediments in the distal eastern part of the basin (Figure 2), we conclude that the basin repeatedly became overfilled with sediments that aggraded above base level. The model was therefore modified to include an overfilled basin with a tapered

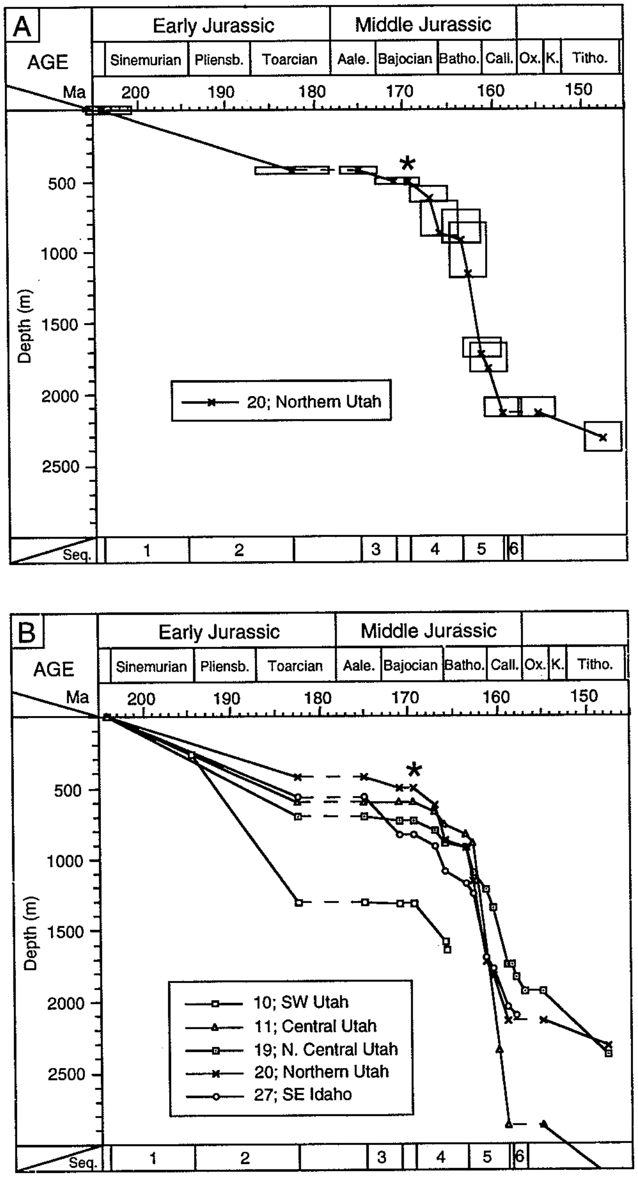
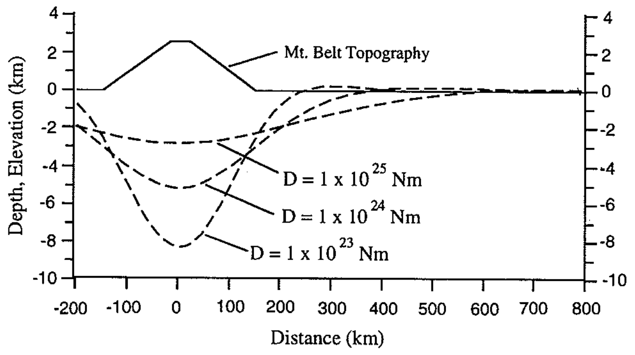


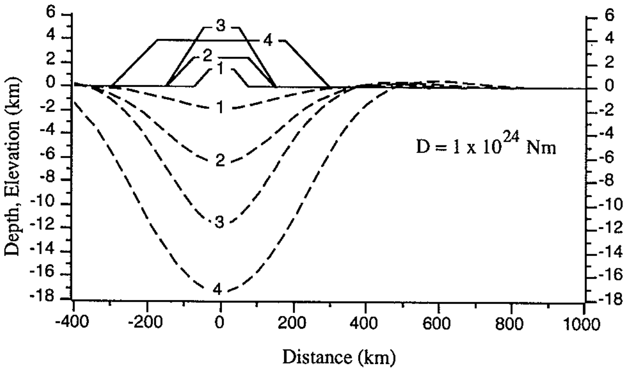
Figure 7. Decompacted subsidence curves for five stratigraphic sections in the Utah-Idaho trough showing the Jurassic time interval. Asterisk marks the onset of rapid Middle Jurassic subsidence. (a) Subsidence curve for section 20, with error bars are shown. Vertical bars represent range of possible values depending on whether or not early cementation of carbonates took place. Horizontal error bars show uncertainty in age due to conversion of biostratigraphic ages. (b) Decompacted subsidence curves for five different sections (locations shown on Figure 1) are shown. Note the overall convex up geometry and segmentation of the curves for Middle Jurassic time. Jurassic data for each section are compiled from *Imlay* [1980] and Triassic and Cretaceous / Tertiary data are from *Hintze* [1988].

alluvial plain on the western side of the basin, which significantly improved the fit between the model and data profiles (Figures 8 and 10). No change was made on the western side of the basic mountain belt topography. The alluvial plain is gently tapered toward the east with surface slopes between 0.07° and 0.14°, which correspond to low gradient alluvial fans and sand bedload streams [*Evans*, 1991]. Basin overfilling effectively redistributes the load out into the basin and flattens the model deflection curve without requiring use of unreasonably large flexural rigidities [*Jordan*, 1981; *Flemings and Jordan*, 1990]. Since dry-system eolian sediments can form accumulations up to several hundred meters thick above the water table [*Kocurek and Havholm*, 1993], sediments in the distal part of the basin were allowed to fill the flexural deflection to an elevated base level 100 m above zero datum. Each sequence is bounded at its top by a regional unconformity, which means that some unknown portion of the stratigraphic record has been removed by later erosion. The stratigraphic analysis suggests that at least 75 m of section were removed at the J-S-up and J-5 unconformities in the distal part of the basin. We account for this unknown missing sediment in the flexural models by making a first-order approximation: stratigraphic thickness profiles (Figure 4) are hung below the model's zero datum, but model sediments are allowed to aggrade above the zero datum to form the tapered alluvial wedge and elevated base level (Figure 10). The thickness discrepancy between the two is assumed to represent sediment removed by erosion at each unconformity (discussed further below).

A. Effects of varying Flexural Rigidity (D)



B. Effects of varying Topographic Load



C. Models Used For This Study (overfilled basin)

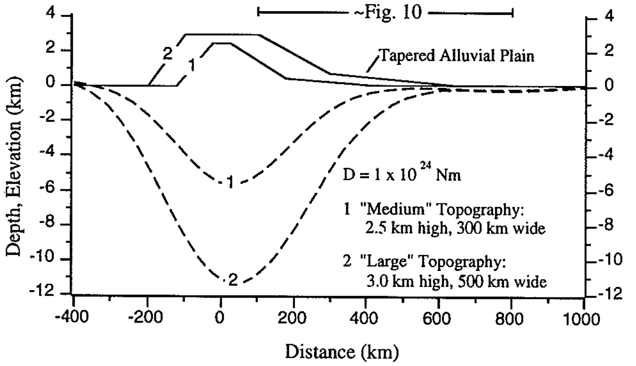


Figure 8. (a) Examples of model flexural subsidence curves assuming a continuous elastic lithosphere, with results for three different values of flexural rigidity (*D*). Weak lithosphere produces a deep narrow basin; strong lithosphere produces a shallow wide basin. (b) Modeled flexural subsidence where flexural rigidity is held constant and the size of the topographic load varies is shown. (c) Topographic profiles used for flexural modeling in this study are shown. Regional topography is approximated from *Saleeby et al.* [1992] and *Jordan* [1981].

Model Results

Figure 10 shows results of first-order flexural modeling in which the model deflections are compared with decompacted stratigraphic profiles of sequence 4 and 5/6, from SW Wyoming to SW Utah. Numerous trial-and-error experiments were performed to produce the best visual fit between the stratigraphic (data) profiles and flexural models. The best match between stratigraphic data and model deflections was obtained using flexural rigidities of 5.0 x 10^{23} to 1.0 x 10^{24} Nm, an overfilled basin, and an elevated base level (100 m) (Figure 10). An infinite elastic plate and overfilling of the basin were required to damp out the outer flexural bulge and widen the depositional basin. These geometries and similar modeling solutions have been employed in other recent modeling studies of foreland basins [*Flemings and Jordan*, 1990; *Jordan and Flemings*, 1991; *Sinclair et al.*, 1991]. Basin overfilling is supported by east directed paleocurrents and fluvial sedimentary facies in the southern Utah-Idaho trough. In the north, regressive marine deposits are directly truncated by regional unconformites J-2, J-S-up, and J-5. We infer that erosion at unconformities removed similar fluvial deposits in the north, and thus the entire basin is treated as overfilled for modeling purposes.

Because stratigraphic thickness profiles are hung below the zero datum, it can be seen that the thickness discrepancy between data and model profiles varies from 100 m in eastern parts of the basin to about 300 m in the west (Figure 10). As each sequence is truncated by unconformities across the entire width of preserved strata (Figure 3), we infer that Middle Jurassic strata in the study area probably were deposited in the distal half of a foreland basin (east of 125 km in Figure 5d; *Jordan and Flemings* [1991]). By comparing the flexural profiles of Figures 9 and 10 with the synthetic model in Figure 5, the flexural profiles can be considered to represent the begin-

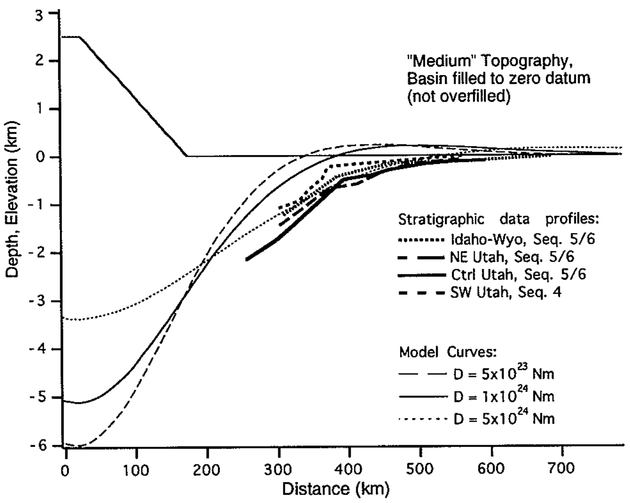


Figure 9. Results of flexural modeling, using "Medium" load topography and filled basin. Model curves do not satisfactorily match stratigraphic data profiles. See text for discussion.

ning of a thrusting episode and the end of quiescence, respectively. We estimate from Figure 9 that forebulge migration might account for 75 to 88% of the observed extent of each sequence-bounding unconformity. Although the simple flexural models presented here cannot account for all of the thickness discrepancies between the data and model profiles in Figure 10, we call attention to the highly continental nature of Middle Jurassic strata and the likelihood that eolian deflation was capable of removing sediment in areas above the water table. Furthermore, because flexural subsidence began in Middle Jurassic time following a long period of quiescence, we speculate that a negative thermal anomaly may have formed in the lithosphere during rapid Middle Jurassic subsidence and sediment infilling [e.g., *Kominz and Bond*, 1986]. Negative thermal anomalies can produce buoyancy forces and a component of uplift in foreland basins [*Kominz and Bond*, 1986]; this also may have contributed to the removal of sediment at unconformities in the western Colorado Plateau region.

The close fit between stratigraphic thickness profiles and model deflections (Figures 10) lends support to earlier inferences that the Utah-Idaho trough formed due to flexural subsidence in a large foreland basin. It is significant that we can duplicate the form of regional stratigraphic profiles using a relatively simple flexural model. The absolute values of model parameters (flexural rigidity, size and geometry of topographic load, geometry of tapered alluvial wedge) should be considered as first-order approximations only. Due to a lack of control on these important model parameters, we focus on the general conclusion obtained from the modeling exercise: flexural modeling combined with stratigraphic and subsidence analysis supports the hypothesis that the Middle Jurassic Utah-Idaho trough formed as a large retroarc foreland basin. Model topography situated to the west of the stratigraphic profiles represents a zone of crustal thickening that was likely created by imbricate thrusting and folding in a Jurassic contractional orogen. The flexural models predict that the eastern edge of the topographic load approximately was located in eastern Nevada during sequence 4 time (169.5 to 164 Ma) (Figure 11) and in western Utah during sequence 5/6 time (163 to 157 Ma). Implications for regional mountain building and magmatism in Nevada and California are discussed below.

Discussion

The preceding conclusions require us to evaluate whether there exists an orogenic belt of the appropriate age that could have caused flexural subsidence in the Utah-Idaho trough during Middle Jurassic time. Our survey of the literature indicates that a broad region of Middle to Late Jurassic contractile deformation can be identified throughout parts of central to western Nevada and southeastern California [e.g., *Saleeby et al.*, 1992]. We have plotted the position of stratigraphic data points and Mesozoic structural features on a tectonic reconstruction for late Middle Jurassic time (Figure 11), which restores Cretaceous contraction and Tertiary extension across the region [*Saleeby et al.*, 1992; *Smith et al.*, 1993]. The magnitude of post-Sevier extension in Nevada is uncertain, adding uncertainty to the Jurassic reconstruction in Figure 11. Recent studies indicate that up to 200 km of Tertiary extension may have occurred in east-central Nevada (Snake Range area) alone [*Gans et al.*, 1989; *Lee et al.*, 1987]. When these possible large amounts of Tertiary extension are added to known extension throughout the rest of the Great Basin [e.g., *Levy and Christie-Blick*, 1989], most Middle Jurassic structures would be restored farther east than their positions in Figure 11. This would improve the fit between model topographic loads and the restored position of thrust belts having a known Jurassic age of deformation.

In the western and central Great Basin, the Luning-Fencemaker fold and thrust belt (LFFT) represents a wide zone of strong Middle to Late Jurassic contraction or transpression with hundreds of kilometres of shortening that occurred east of the active Cordilleran magmatic arc (Figures 1 and 11) [*Oldow*, 1984, 1993; *Speed et al.*, 1988; *Dilek and Moores*, 1993]. In the western part of the Luning-Fencemaker fault system, rocks that experienced ductile deformation at greenschist to amphibolite facies conditions are cut by postkinematic 169 Ma plutons (U-Pb) [*Oldow*, 1993]. The restored position of the Luning-Fencemaker fold-thrust belt coincides roughly with the western and central part of the modeled orogenic load (Figure 11). Other possible sources of crustal loading in the Great Basin include the central Nevada thrust belt in the vincinity of the Eureka Belt (EB), a large belt of contractile deformation that could have been active any time between Permian and early Cretaceous time (Figure 1 and 11) [*Taylor et al.*, 1993]. Probable Jurassic tectonic thickening of up to 10-20 km has been documented from the Ruby Mountains (RM) and East Humbolt Range, which make up the northern continuation of the central Nevada thrust belt [*Hodges et al.*, 1992]. The "Elko Orogeny" [*Thorman et al.*, 1992] consists of possible Middle Jurassic folds and thrusts that may have contributed to crustal loading in this region. *Miller and Hoisch* [1992] have questioned the likelihood of widespread contractional deformation in eastern Nevada, citing geobarometric data that preclude deep burial of rocks in northeastern Nevada and northwestern Utah during this time. Based on the presence of thrusts and folds in this area that predate 165-155 Ma [*Miller and Hoisch*,

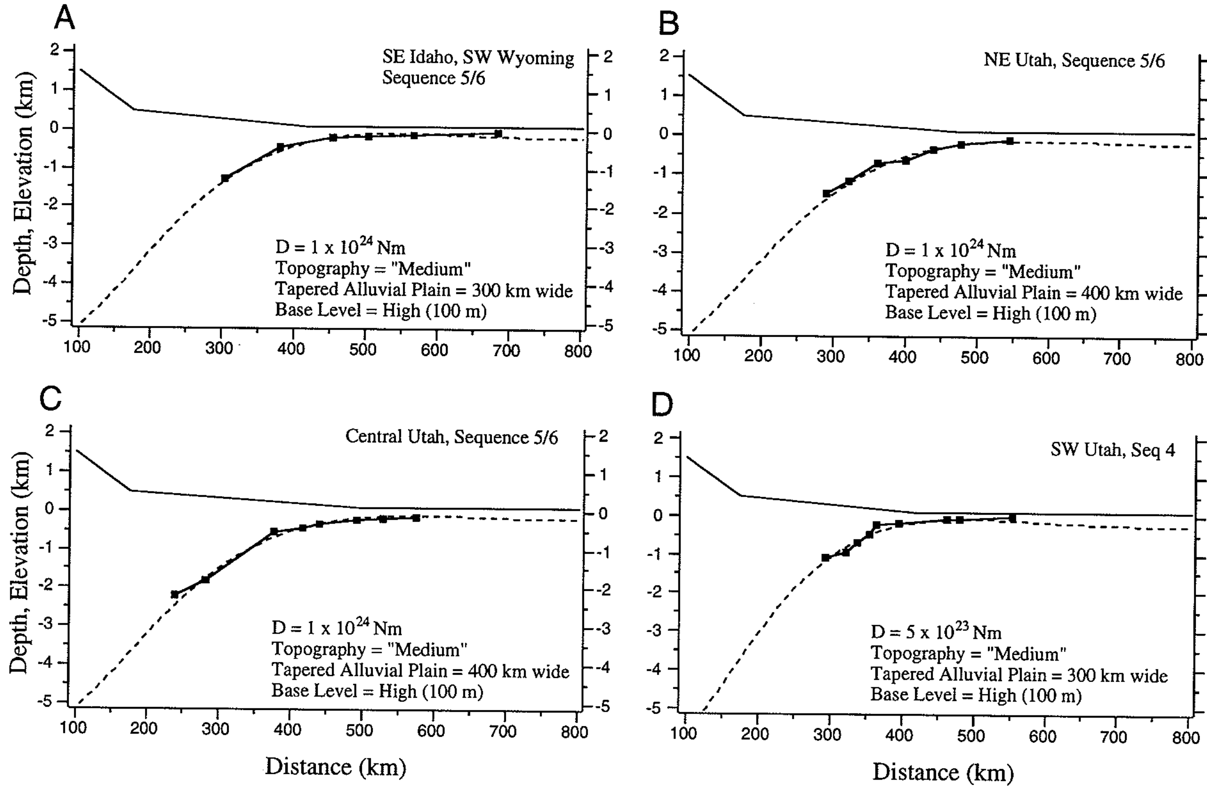


Figure 10. Results of flexural modeling using "Medium" load topography and an overfilled basin. Dashed lines represent the best fit model curve; boxes and solid lines represent the stratigraphic data profiles. Models using a "Large" load topography are not shown because they are similar to curves shown here. Data profiles and their locations are shown in Figures 4 and 1, respectively. See text for discussion.

1992], we suggest that crustal thickening in northeastern Nevada may have occurred prior to pluton emplacement. For example, it appears that crustal shortening in the Newfoundland Mountains (NM) of northwestern Utah took place prior to pluton emplacement at about 150 Ma [*Allmendinger and Jordan*, 1984].

In east-central California (east Sierran thrust system (ESTS), Figures 1 and 11), Middle to Upper Jurassic strata were tilted and folded during one or more episodes of Middle to Late Jurassic contractile deformation (minimum ages 150 to 148 Ma) [*Dunne and Walker*, 1993; *Dunne et al.*, 1994]. In the Central Mojave Desert of southeastern California, *Walker et al.* [1990] documented SE vergent contractile deformation between 169 and 154 Ma. At other locations in the Central Mojave Desert, intermediate-grade metamorphism, thrust faults, and folds have been documented with deformation occurring approximately between 187 and 148 Ma [*Boettcher and Walker*, 1993]. Based on these studies, it appears that a broad belt extending from central and western Nevada through east central California to the Mojave Desert experienced protracted crustal thickening and tectonic loading during one or several episodes of contractile deformation during Middle to Late Jurassic time (Figures 1 and 11).

The question of whether the Jurassic Cordilleran orogen was a high-relief Andean-type arc [*Burchfiel and Davis*, 1972] or a series of low-relief arc-graben depressions [*Busby-Spera*, 1988] continues to be debated. Flexural models used in this study require a sizable regional topography (2.5 km high; 300 km wide) to obtain a match with the stratigraphic data. Studies that support Middle Jurassic tectonic thickening and crustal loading are summarized above. A hypothesis by *Schermer* [1993], which invokes along-strike variations in structural style to explain apparent discrepancies in the style of arc deformation, provides an intriguing potential solution to disagreements over the issue of a high versus low topography in the arc-orogen.

Recent studies have argued that Middle Jurassic strata could not have been deposited in a typical foreland basin because the succession is thin and only a minor percentage of strata are coarse grained [*Miller and Hoisch*, 1992; *Lawton*, 1994]. Our model approximations and sediment decompactions indicate, however, that the studied sequences can account for the distal ~2/3 of a flexural foreland basin using reasonable model parameters. We infer that a large volume of coarse-grained sediments was removed from the proximal part of the Utah-Idaho trough by erosion that produced the K-1 unconformity (Figure 3). Erosion of the Cordilleran orogen and proximal part of the foreland basin probably began during deposition of the Morrison Formation in Late Jurassic time, as indicated by the presence of far travelled, westerly derived Paleozoic chert clasts [*Peterson*, 1986, 1988b]. Assuming that erosion of proximal Middle Jurassic strata began during Late Jurassic

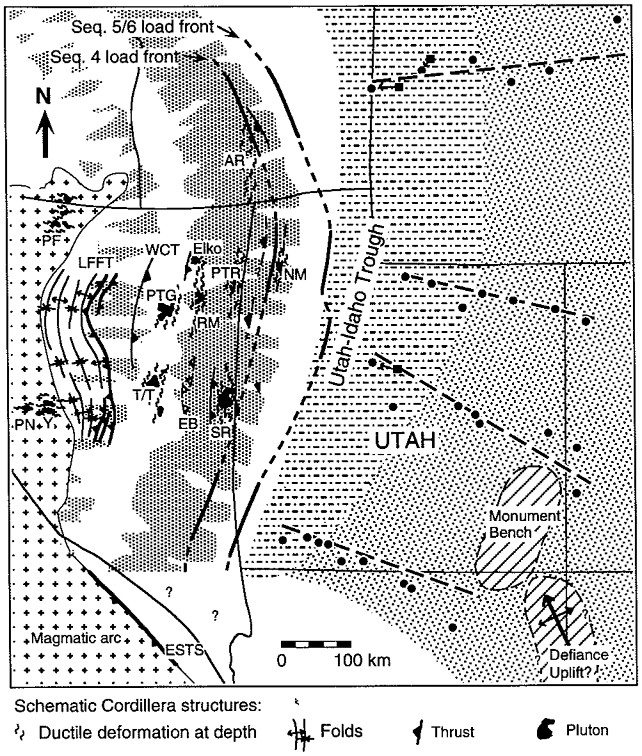


Figure 11. Schematic reconstruction of Cordilleran tectonics and paleogeography for late Middle Jurassic time, after *Saleeby et al.* [1992] and *Smith et al.* [1993]. Eastern edge (thick dashed lines) and elevations (schematic shading) of model crustal load ("Medium" topography, Figure 10) are shown for sequences 4 and 5/6. Middle to Late Jurassic Cordilleran structures are AR, Albion Range; EB, Eureka Belt; ESTS, East Sierra thrust system; LFFT, Luning-Fencemaker fold and thrust belt; NM, New Foundland Mountains; PF, Pine Forest Range; PN, Pine Nut Range; PTG, Pony Trail Group; PTR, Pilot-Toana Range; RM, Ruby Mountains; SR, Snake Range; T/T, Toiyabe-Toquima Range; WCT, Willow Creek thrust; Y, Yerington.

time, and if the basal Cretaceous Buckhorn Conglomerate transported some of the Jurassic sediments [*Heller and Paola*, 1989; *Yingling and Heller*, 1992], 37 m.y. would be available for erosion to take place. This gives denudation rates between 100 and 450 mm/kyr, which is reasonable compared to typical mountain range denudation rates of 50 to 500 mm/kyr [*Kukal*, 1990].

It appears that crustal loading in orogenic terranes to the west, and resultant flexural subsidence in the Utah-Idaho trough, had begun by middle Bajocian time (169 Ma) (Figure 7). If we take the J-1 unconformity to record initiation of thrusting, then we would conclude that thrust loading began by middle Aalenian time, about 175 Ma (Figures 3 and 7). In southwest Utah there appears to be an earlier acceleration in subsidence during Sinemurian to Pliensbachian time (~194 Ma; Figure 7b) [*Verlander*, 1994], which may indicate that orogenic loading occurred earlier in southern Nevada and southeastern California than in the north. At approximately 157 Ma, following 10 to 15 m.y. of rapid subsidence, the rate of Middle Jurassic subsidence decreased (Figure 7). This decrease in subsidence rate probably resulted from a hiatus in contractional tectonism, which may have produced known Late Jurassic extension, normal faulting and gravitational collapse of the orogenic wedge [*Allmendinger and Jordan*, 1984; *Miller and Hoisch*, 1992; *Molnar and Lyon-Caen*, 1988]. Alternatively, it is possible that episodes of shortening and extension alternated on a relatively short timescale throughout much of Middle Jurassic time, a type of structural behavior that is common in convergent margins [*Dalmayrac and Molnar*, 1981]. If this were the case, we believe that contraction-related crustal thickening dominated over extension and that the thrust-generated crustal load in central and eastern Nevada was sufficient to create the Utah-Idaho trough as a retroarc foreland basin.

Conclusions

Broad, uniform Early Jurassic subsidence (sequence 1/2) across most of the study area is tentatively attributed to slow lithospheric cooling and sediment loading, but the possibility of synorogenic asymmetric subsidence during this time is acknowledged. Until better absolute age dates are obtained, basin-forming processes for Early Jurassic time will remain uncertain.

A major change in basin configuration occurred in early Middle Jurassic time, at least by 170 Ma and possibly as early as ~175 Ma (J-1 unconformity). This change marks the onset of pronounced asymmetric subsidence toward the west, which formed the deep sedimentary basin known as the Utah-Idaho trough. Subsidence rates increased substantially at this time through-out the region from southwestern Utah to Idaho. Changes in the rate and geometry of basin subsidence are attributed to the onset of flexural subsidence in a retroarc foreland basin, which was produced by crustal loading in the arc-orogen to the west.

Stratal geometries of Middle Jurassic sedimentary sequences appear to have been controlled by episodic thrusting in an orogenic fold-thrust belt to the west. We suggest that the Middle Jurassic unconformities (J-1, J-2, J-S-up, and J-5) formed by erosion of an outer flexural bulge that migrated laterally though time in response to episodic thrusting to the west.

Numerical flexural modeling supports the hypothesis that the Middle Jurassic Utah-Idaho trough was a retroarc foreland basin. These results suggest that the orogenic belt probably had moderate topographic relief, with an eastern thrust front that was located in eastern Nevada during sequence 4 time (170 to ~164 Ma) and in western Utah during sequence 5/6 time (~163 to ~157 Ma). The position of the modeled orogenic load roughly coincides with reconstructed belts of Middle Jurassic contractional deformation documented in other studies.

In early Late Jurassic time (~157 Ma; J-5 unconformity) the rate of subsidence slowed; this marks the beginning of a period of quiescence in the orogen that lasted until the Sevier Orogeny. This hiatus in contractional tectonism may have caused gravitational collapse of the orogenic wedge and crustal extension on normal faults, as recorded in late Middle Jurassic to early Late Jurassic (165-155 Ma) extensional structures in western Utah.

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C. J. Bjerrum, Geological Institute, University of Copenhagen, Oester Voldgade 10, DK-1350 Copenhagen K., Denmark. (e-mail: christianjb@geo.geol.ku.dk)

R. J. Dorsey, Department of Geology, Northern Arizona University, Box 4099, Flagstaff, Az 86011. (e-mail: dorsey@nauvax.ucc.nau.edu)

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