Subsidence analysis of the Cordilleran miogeocline: Implications for timing of late Proterozoic rifting and amount of extension

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ABSTRACT

Tectonic subsidence of the Cordilleran miogeocline in the western United States during late Proterozoic through early Paleozoic time is best explained by rifting and subsequent thermal contraction of the lithosphere. The tectonic component of subsidence can be calculated by removing the isostatic effects of sediment and water loading. The resultant subsidence curves indicate that rifting began about 600 m.y. ago and that extension of the lithosphere during rifting was in excess of a factor of 1.3.

INTRODUCTION

Sedimentary rocks of the Cordilleran miogeocline constitute a relatively complete record of subsidence along an ancient rifted continental margin. The time when rifting began is not constrained by paleontological evidence because lower miogeoclinal strata consist mostly of unfossiliferous Proterozoic siliciclastic rocks. Thus, the time of rifting is a controversial issue. To complicate matters, the western margin of North America may have undergone multiple episodes of rifting (Burchfiel and Davis, 1975); however, this report concerns only the final rifting phase that began in the late Proterozoic, probably long after inferred earlier episodes of continental extension.

The driving force of subsidence of the Cordilleran miogeocline probably was related to lithospheric attenuation during rifting. Thinning of the lithosphere is thought to cause initial (synrift) subsidence to maintain isostatic equilibrium, and also later thermal (postrift) subsidence as the thinned lithosphere cools to its equilibrium thickness (McKenzie, 1978). McKenzie formulated a model for subsidence of rifted continental margins using simple lithospheric stretching, isostatic adjustment, and thermal equilibration, and he derived magnitudes of tectonic subsidence according to amounts of lithospheric extension. However, total subsidence of sedimentary basins is an integrated result of sediment and water loading as well as tectonic subsidence. To isolate the tectonic component of subsidence through time, therefore, the cumulative contributions of isostatic sediment and water loads must be removed by a technique called backstripping (Steckler and Watts, 1978). Tectonic subsidence can then be compared to theoretical models.

Here, we analyze the early Paleozoic history of subsidence of the Cordilleran miogeocline in order to interpret the time of latest Proterozoic rifting and amount of lithospheric extension. This is done by backstripping four key stratigraphic sections distributed across this ancient continental margin (Fig. 1).

GEOLOGIC SETTING

Upper Proterozoic through lower Mesozoic miogeoclinal strata in the western United States, locally as thick as 15 km, accumulated along a broad continental terrace that developed when North America rifted from another continental landmass (Stewart, 1976). During late Proterozoic through Early Cambrian time, the miogeocline subsided rapidly and received an enormous quantity of mostly siliciclastic material. Subsidence continued during Middle Cambrian through Middle Devonian time, when mostly carbonate and minor siliciclastic sediments were deposited (Stewart and Poole, 1974). The Cordilleran miogeocline was characterized by remarkable continuity of lithofacies and thickness along depositional strike throughout this time.

The rifted-margin pattern of sedimentation was interrupted by the Antler orogeny in Late Devonian to Early Mississippian time, when basinal marine rocks were thrust eastward over coeval miogeoclinal rocks along the Roberts Mountains thrust. An elongate foreland basin developed east of the leading edge of the thrust belt but was filled in by Late Mississippian time, after which mostly shallow-marine deposition resumed (Harbaugh and Dickinson, 1981). The Cordilleran miogeocline persisted, even through the Sonoma orogeny in Late Permian through Early Triassic time, and continued to receive sediments until the Sevier orogeny, which commenced as early as Late Jurassic time.

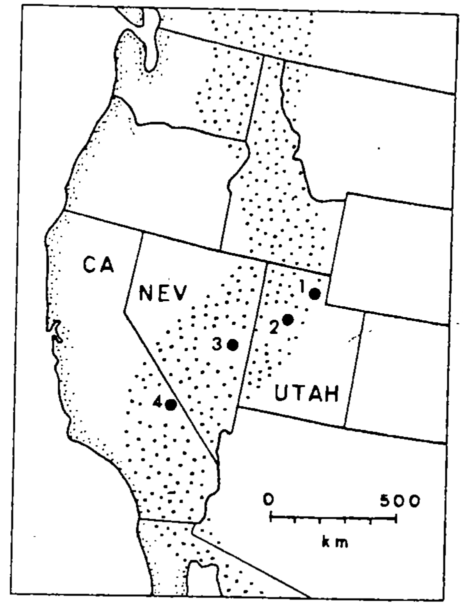

Figure 1. Map showing Cordilleran miogeocline (heavy stipple) and locations of stratigraphic sections used for this study. 1 = Huntsville area (Crittenden et al., 1971; Deiss, 1938; Hintze, 1973; Maxey, 1958; Williams, 1948), 2 = Sheeprock Mountains (Christie-Blick, 1982; Cohenour, 1959; Hintze, 1973), 3 = Ely area (Boettcher and Sloan, 1960; Langenheim and Larson, 1973; Misch and Hazzard, 1962), and 4 = Panamint Range (Hopper, 1947; Langenheim and Larson, 1973; Stewart, 1970).

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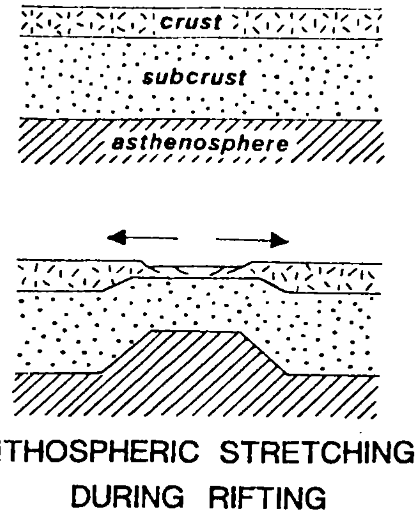

Figure 2. McKenzie's (1978) model for extension of lithosphere by stretching and thinning. Top figure shows prerift lithosphere and asthenosphere.

RIFTED MARGIN MODELS

The great thickness of shallow-water sediments deposited at many rifted continental margins has been explained by various models. The most widely embraced of these models involve thermal contraction of the lithosphere following rifting (e.g., Sleep, 1971; McKenzie, 1978; Royden et al, 1980; Beaumont et al., 1982). McKenzie (1978) suggested that the lithosphere undergoes passive uniform stretching during rifting. In his model, initial subsidence results from isostatic adjustment due to the upward rise of hot asthenosphere (Fig. 2), followed by contractional subsidence as the lithosphere cools. McKenzie's model of simple extension and thermal contraction adequately fits most empirical constraints (Watts, 1981), and we incorporate his model in our estimates of lithospheric stretching and time of rifting.

GEOHISTORY AND BACKSTRIPPING

Analysis of subsidence of the Cordilleran miogeocline was accomplished by backstripping stratigraphic sections. Backstripping is a technique to calculate isostatic subsidence through time by iteratively removing loads of sediment and water. The residual component of subsidence not explained by isostatic loading is ascribed to tectonic causes and in this study was compared to predictions based on McKenzie's model of tectonic subsidence for thinned lithosphere.

The data needed for backstripping for the local-loading model of isostasy are thickness and age of strata and paleobathymetry for selected stratigraphic intervals for the section under consideration. Eustatic changes in sea level were not considered, being difficult to estimate for late Proterozoic and Paleozoic time. In the local-loading model, the crust cannot support shear stress imposed by loading, and thus lateral strength of the lithosphere is ignored. The effect of isostatic loading is therefore maximized, and tectonic subsidence is correspondingly minimized.

Compaction that occurs during burial can be estimated from changes in porosity as a function of lithology and burial depth (Van Hinte, 1978). Backstripping with compaction corrections thereby allows construction of geohistory diagrams (Van Hinte, 1978) that depict subsidence versus time for stratigraphic sections (Fig. 3).

Stratigraphic sections of the Cordilleran miogeocline are well suited for backstripping and geohistory analysis because of a relatively complete stratigraphic record for which there is good biostratigraphic control. Although the miogeocline was deformed during Sevier thrusting and Basin-and-Range extension, coherent stratigraphic units are well preserved within domains that are internally little deformed. Absolute ages keyed to biostratigraphy were obtained from the Correlation of Stratigraphic Units of North America (COSUNA; O. Childs, ed., in prep.) time scale. Paleowater depths were estimated for each interval by considering lithofacies.

Four stratigraphic sections were examined for this study: (1) Huntsville, Utah (composite section), (2) Sheeprock Mountains, Utah, (3) Ely, Nevada (composite section, including McCoy Creek Group), and (4) Panamint Range, California. All of these stratigraphic sections seem relatively complete, and none are within metamorphic core complexes where stratigraphic attenuation has occurred.

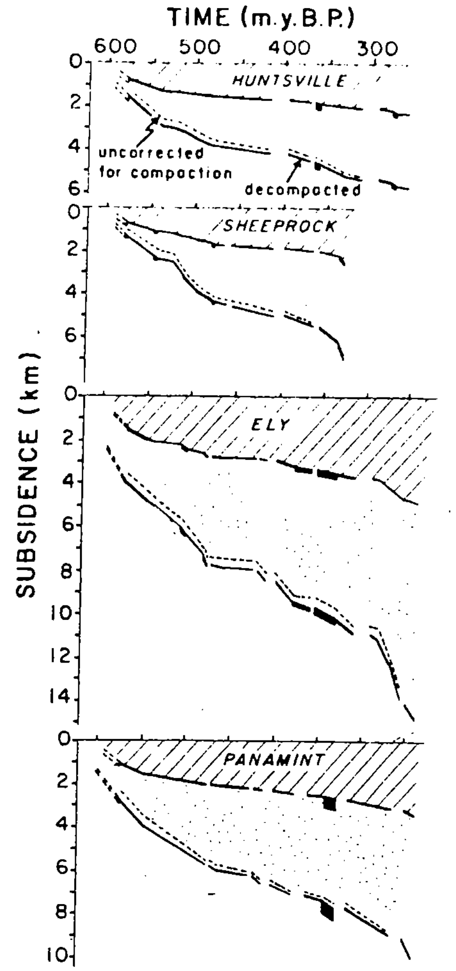

Figure 3. Geohistory diagrams for Huntsville area, Sheeprock Mountains, Ely area, and Panamint Range. Total subsidence curves are beneath stippled area, and tectonic subsidence curves are beneath hachured area. Range of uncertainty of paleowater depths shown by thickness of line segments for cumulative total subsidence and tectonic subsidence. Gaps in subsidence curves show unconformities. Dashed lines near origin of each diagram represent unfossiliferous upper Proterozoic rocks.

The oldest sedimentary rocks included in our analysis are the predominantly siliciclastic rocks of late Proterozoic age. Underlying middle Proterozoic rocks and upper Proterozoic diamictite and associated shale and volcanic rocks are excluded. Upper Proterozoic diamictite, of glacial origin (Crittenden et al., 1983), and associated rocks probably were deposited before rifting from which the Cordilleran miogeocline took form. Even though the diamictite-volcanic assemblage is widespread in the Cordillera, it crops out only in a few localities, commonly overlying middle Proterozoic sedimentary rocks or Archean basement, or, where its base is not exposed, occurring within or near inferred epicratonic troughs in the western margin of North America where middle Proterozoic rocks were deposited (Stewart, 1976). This seems more than just a fortuitous circumstance of preservation or exposure, and it indicates that the diamictite-volcanic assemblage probably was deposited in reactivated or remnant troughs filled with middle Proterozoic rocks, before latest Proterozoic rifting of the miogeocline.

The age of the diamictite-volcanic assemblage is uncertain but seems to be much older than uppermost Proterozoic miogeoclinal rocks. Radiometric dates of rocks that possibly are correlative to the diamictite-volcanic assemblage range from about 770 m.y. (Armstrong et al., 1982) to

918 m.y. (Miller et al., 1973) (929 m.y. with new radiometric constants; J. W. Welty, 1983, personal commun.). Still other interpretations are possible for the relationship between the diamictite-volcanic assemblage and undoubted miogeoclinal rocks. For example, Miller (1983) reported interfingering beds of diamictite and miogeoclinal marine shelf strata in the Panamint Range, where this contact previously was regarded to mark a profound unconformity.

RESULTS AND DISCUSSION

Amount of Extension

The tectonic subsidence curves (Fig. 4) indicate that subsidence prior to the Antler orogeny is similar to McKenzie's model curves for a stretched lithosphere. For the Huntsville and Sheeprock Mountains sections the tectonic subsidence curves closely match model curves with stretching values (β) of 1.3. For the Ely and Panamint Range sections, β values are between 1.5 and 1.7. Higher values in the western sections indicate greater stretching of lithosphere beneath more seaward parts of the Cordilleran miogeocline.

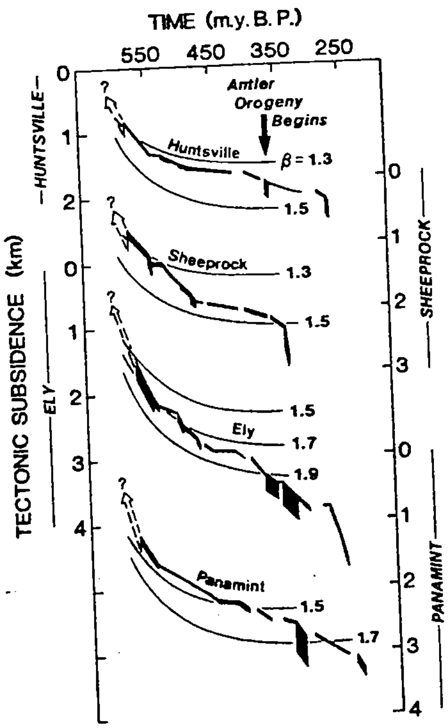

Figure 4. Tectonic subsidence curves for Huntsville area, Sheeprock Mountains, Ely area, and Panamint Range, calculated from local-loading model of isostasy compared with theoretical tectonic subsidence curves of McKenzie (1978) for crust that is initially 30 km thick. Factors of extension (β) are indicated by each theoretical tectonic subsidence curve. Range of uncertainty of paleowater depths indicated by thickness of line segments. Time of initial tectonic subsidence and deposition of basal upper Proterozoic rocks is speculative, as indicated by queries.

Stretching values of 1.3 to 1.7 (lithospheric attenuation by 20% to 40%) for the Cordilleran miogeocline are less than those generally obtained for the Atlantic margin, which is an analog of similar scale. These apparently low stretching values for the Cordilleran miogeocline are partly due to the local-loading isostatic model for backstripping that minimizes tectonic subsidence, but also they may reflect the shortcomings of a simple stretching model.

Two regimes of sedimentation are predicted by McKenzie's model: synrift sedimentation during isostatic adjustment of thinned lithosphere, followed by postrift deposition as the lithosphere cools and subsides. Initial subsidence corresponding to these estimates of 1.3 to 1.7 for stretching would allow deposition of about 0.8 to 1.6 km of synrift strata, shown in Figure 4 by depth to beginning of McKenzie's model curves for thermally subsiding lithosphere. In the Cordilleran miogeocline, however, it is difficult if not impossible to distinguish synrift sequences from postrift sequences. An expected boundary between these sequences is a breakup unconformity, but this has not been recognized.

Time of Rifting

Given a predictable rate of lithosphere contraction and tectonic subsidence of the Cordilleran miogeocline, it is possible to estimate the onset of latest Proterozoic rifting by matching theoretical thermal curves to tectonic subsidence curves calculated by backstripping. Using the curve-fitting method, the absolute age of upper Proterozoic rift strata can be estimated, and hence the time of rifting (time of "instantaneous" subsidence according to McKenzie's model). Instantaneous subsidence and synrift deposition obviously are contrivances of the model, but early subsidence of the miogeocline probably was rapid. Evidence of rapid early subsidence is provided by the fit of tectonic subsidence curves to McKenzie's model curves. A protracted rifting event would result in much cooling of the lithosphere during the synrift phase, and therefore the postrift thermal subsidence would be considerably diminished and would not behave according to the theoretical curves of McKenzie. In general, the theoretical curves most closely fit the tectonic curves when initial (instantaneous) subsidence began at about 590 m.y. ago (Fig. 4), and thus rifting probably commenced only a few million years prior to that, probably not much earlier than 600 m.y. ago. These results are similar to those of Bond and Kominz (1983), who estimated that continental separation occurred sometime between 550 and 600 m.y. ago, on the basis of a backstripping study of miogeoclinal strata in the southern Canadian Rocky Mountains; they are also comparable to estimates by Stewart and Suczek (1977) of between 600 and 650 m.y. ago for latest Proterozoic rifting. Time scales used in both of those studies are not appreciably different for the early Paleozoic from the COSUNA time scale used for this study.

There is a linear relation between tectonic subsidence and square root of time since rifting, assumed to be 600 m.y. ago, for about the first 150 m.y. after initial rifting (Fig. 5). This is the predicted result from a cooling lithosphere model (Turcotte and Ahern, 1977). For each stratigraphic section except the Sheeprock Mountains, the linear relation can be divided arguably into two line segments, representing two phases of thermal subsidence. More data points are needed to substantiate the paired line segments, but the time at which the steeper lines intersect the more gently inclined lines is about the same in each case. In Figure 5 the bend in the lines corresponds to about 60 m.y. after rifting. These results are comparable with those of Keen (1979), who demonstrated a linear relation of subsidence and square root of time for part of the Canadian Atlantic margin. Keen also noted a change in rate of subsidence versus square root of time at about 80 m.y. after rifting of the Atlantic, at which time the lithosphere probably attained a critical thickness, so a slower

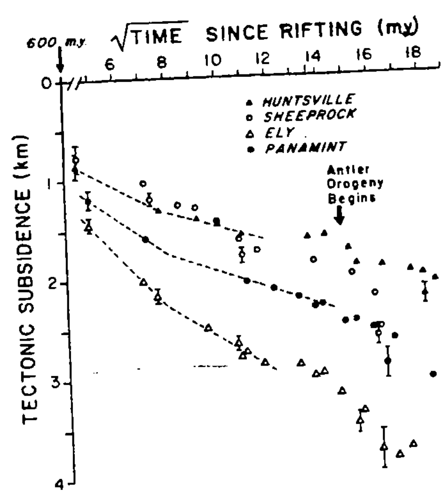

Figure 5. Tectonic subsidence plotted against square root of time. Dashed straight lines visually fit to data points for all stratigraphic sections except Sheeprock Mountains. Error bars reflect uncertainty of paleo-water depths.

...al subsidence rate began. However, another possibility is that the bend in the lines in Figure 5 is an artifact of the COSUNA time scale.

The point at which tectonic subsidence and square root of time are no longer linearly related corresponds approximately to the time at which McKenzie's theoretical curves begin to flatten out. Therefore, thermally driven subsidence of the Cordilleran miogeocline seems to have reduced significance after about 150 m.y. following rifting. Regional unconformities record erosion or nondeposition in the miogeocline during the Middle and Late Ordovician and Early and Late Silurian. The unconformities occurred when subsidence was considerably diminished, perhaps when the miogeocline began to be extremely sensitive to extrabasinal influences such as eustatic sea-level changes. In Figure 4 tectonic subsidence curves show slight downward inflections at about 40 to 50 m.y. before the Antler orogeny, perhaps foreshadowing that event. Radical departures of the tectonic subsidence curves from the model curves occur at about the start of the Antler orogeny, in Late Devonian time (Figs. 4, 5).

CONCLUSIONS

Sedimentary rocks of the Cordilleran miogeocline provide an excellent opportunity to assess tectonic subsidence of this ancient rifted margin quantitatively. Tectonic subsidence curves calculated by backstripping four stratigraphic sections resemble theoretical subsidence curves of a uniformly stretched lithosphere. Uniform lithospheric stretching by minimum factors of 1.3 to 1.7, or thinning by 20% to 40%, would account for the observed subsidence. Latest Proterozoic rifting of the Cordilleran miogeocline probably started about 600 m.y. ago.

REFERENCES CITED

Armstrong, R. L., Eisbacher, G. H., and Evans, P. D., 1982, Age and stratigraphic-tectonic significance of Proterozoic diabase sheets, Mackenzie Mountains, northwestern Canada: Canadian Journal of Earth Sciences, v. 19, p. 316–323.

Beaumont, C., Keen, C. E., and Boutilier, R., 1982, On the evolution of rifted continental margins: Comparisons of models and observations for the Nova Scotian margin: Royal Astronomical Society Geophysical Journal, v. 70, p. 667–715.

Boettcher, J. W., and Sloan, W. W., eds., 1960, Geology of east-central Nevada: Intermountain Association of Petroleum Geologists and Eastern Nevada Geological Society, 11th Annual Field Conference, Guidebook, 278 p.

Bond, G. C., and Kominz, M. A., 1983, Thermal-mechanical modeling of early Paleozoic miogeoclinal sequences in southern Canadian Rockies [abs.]: American Association of Petroleum Geologists Bulletin, v. 67, p. 427.

Burchfiel, B. C., and Davis, G. A., 1975, Nature and controls of Cordilleran orogenesis, western United States: Extensions of an earlier synthesis: American Journal of Science, v. 275-A, p. 363–396.

Christie-Blick, N., 1982, Upper Proterozoic and Lower Cambrian rocks of the Sheeprock Mountains, Utah: Regional correlation and significance: Geological Society of America Bulletin, v. 93, p. 735–750.

Cohenour, R. E., 1959, Sheeprock Mountains, Tooele and Juab Counties: Utah Geological and Mineralogical Survey Bulletin 63, 201 p.

Crittenden, M. D., Jr., Schaeffer, F. E., Trimble, D. E., and Woodward, L. A., 1971, Nomenclature and correlation of some upper Precambrian and basal Cambrian sequences in western Utah and southeastern Idaho: Geological Society of America Bulletin, v. 82, p. 581–602.

Crittenden, M. D., Jr., Christie-Blick, N., and Link, P. K., 1983, Evidence for two pulses of glaciation during the late Proterozoic in northern Utah and southeastern Idaho: Geological Society of America Bulletin, v. 94, p. 437–450.

Deiss, C., 1938, Cambrian formations and sections in part of Cordilleran trough: Geological Society of America Bulletin, v. 49, p. 1067–1168.

Harbaugh, D. W., and Dickinson, W. R., 1981, Depositional facies of Mississippian clastics, Antler foreland basin, central Diamond Mountains, Nevada: Journal of Sedimentary Petrology, v. 51, p. 1223–1234.

Hintze, L. F., 1973, Geologic history of Utah: Brigham Young University Geology Studies, v. 20, 181 p.

Hopper, R. H., 1947, Geologic section from the Sierra Nevada to Death Valley, California: Geological Society of America Bulletin, v. 58, p. 393–432.

Keen, C. E., 1979, Thermal history and subsidence of rifted continental margins: Evidence from wells on the Nova Scotia and Labrador shelves: Canadian Journal of Earth Sciences, v. 16, p. 505–522.

Langenheim, R. L., and Larson, E. R., 1973, Correlation of Great Basin stratigraphic units: Nevada Bureau of Mines and Geology Bulletin 72, 36 p.

Maxey, G. B., 1958, Lower and Middle Cambrian stratigraphy in northern Utah and southeastern Idaho: Geological Society of America Bulletin, v. 69, p. 647–688.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32.

Miller, F. K., McKee, E. H., and Yates, R. G., 1973, Age and correlation of the Windermere Group in northeastern Washington: Geological Society of America Bulletin, v. 84, p. 3723–3730.

Miller, J.M.G., 1983, Upper Precambrian unconformity within the Kingston Peak Formation, Panamint Range, eastern California: Geological Society of America Abstracts with Programs, v. 15, p. 424.

Misch, P., and Hazzard, J. C., 1962, Stratigraphy and metamorphism of late Precambrian rocks in central northeastern Nevada and adjacent Utah: American Association of Petroleum Geologists Bulletin, v. 46, p. 289–343.

Royden, L., Sclater, J. G., and von Herzon, R. P., 1980, Continental margin subsidence and heat flow: Important parameters in formation of petroleum hydrocarbons: American Association of Petroleum Geologists Bulletin, v. 64, p. 173–187.

Sleep, N. H., 1971, Thermal effects of the formation of Atlantic continental margins by continental breakup: Royal Astronomical Society Geophysical Journal, v. 25, p. 325–330.

Steckler, M. S., and Watts, A. B., 1978, Subsidence of the Atlantic-type continental margin off New York: Earth and Planetary Science Letters, v. 41, p. 1–13.

Stewart, J. H., 1970, Upper Precambrian and Lower Cambrian strata in the southern Great Basin, California and Nevada: U.S. Geological Survey Professional Paper 620, 206 p.

—— 1976, Late Precambrian evolution of North America: Plate tectonics implications: Geology, v. 4, p. 11–15.

Stewart, J. H., and Poole, F. G., 1974, Lower Paleozoic and uppermost Precambrian miogeocline, Great Basin, western United States, *in* Dickinson, W. R., ed., Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 28–57.

Stewart, J. H., and Suczek, C. A., 1977, Cambrian and latest Precambrian paleogeography and tectonics in the western United States, *in* Stewart, J. H., et al., eds., Paleozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 1, p. 1–17.

Turcotte, D. L., and Ahern, J. L., 1977, On the thermal and subsidence history of sedimentary basins: Journal of Geophysical Research, v. 82, p. 3762–3766.

Van Hinte, J. E., 1978, Geohistory analysis—Application of micropaleontology in exploration geology: American Association of Petroleum Geologists Bulletin, v. 62, p. 201–222.

Watts, A. B., 1981, The U.S. Atlantic continental margin: Subsidence history, crustal structure, and thermal evolution: American Association of Petroleum Geologists Education Course Note Series Number 19, p. 2-1–2-75.

Williams, J. S., 1948, Geology of the Paleozoic rocks, Logan quadrangle, Utah: Geological Society of America Bulletin, v. 59, p. 1121–1164.

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