Two diamictites, two cap carbonates, two $\delta^{13}C$ excursions, two rifts: The Neoproterozoic Kingston Peak Formation, Death Valley, California

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ABSTRACT

Stratigraphic mapping of the Neoproterozoic glaciogenic Kingston Peak Formation (Death Valley, California) provides evidence for two temporally discrete extensional deformation episodes. These episodes are bracketed by the Sourdough Limestone and Noonday Dolomite, the facies characteristics and $\delta^{13}C$ data (ranging between 2.15 and –2.56‰ and –1.88 and –4.86‰, respectively) of which make them equivalent to Sturtian and Varangian age cap carbonates, respectively. This constrains the two extensional episodes along the southwestern margin of Laurentia to ca. 700 Ma and ca. 600 Ma. These observations and data show that the field evidence for mid-Neoproterozoic breakup and the predictions from tectonic subsidence curves for a latest Neoproterozoic breakup are both correct. Thus, Neoproterozoic plate reconstructions must account for two discrete rift episodes separated by 100 m.y. or more. Confining rifting to within the Kingston Peak Formation thereby places the younger Proterozoic rocks of the southwestern Great Basin in the rift to drift tectonic phase.

INTRODUCTION

The Neoproterozoic breakup of the Rodinian supercontinent and subsequent amalgamation of Gondwana is a well-accepted hypothesis. However, the timing of Rodinia fragmentation around its Laurentian thorax remains problematic (Dalziel, 1997). In 1972, Jack Stewart proposed that late Precambrian diamictite and volcanic rocks exposed intermittently along the North American Cordillera were synrift deposits and that, because such rocks occurred on both margins of Laurentia, rifting was cratonwide (Stewart, 1976). Field constraints place this rifting at 700–800 Ma (Bond et al., 1985; Ross, 1991; Young, 1995), but tectonic subsidence curves imply a much later final thermal event, ca. 550–600 Ma (Bond and Kominz, 1984; Levy and Christie-Blick, 1991). Either two discrete rifts or protracted rifting occurred (Bond, 1997; Young, 1995). The purpose of this paper is to present newly obtained data on the Neoproterozoic glaciogenic Kingston Peak Formation in the Death Valley region of California that support the model for two discrete rifting episodes and provide ages for Kingston Peak glaciations.

STRATIGRAPHIC DATABASE

The Kingston Peak Formation is typical of the inferred synrift glaciogenic rocks preserved along the North American Cordillera. It is as thick as 3 km, exhibits abrupt facies and thickness changes, contains diamictite, and was deposited in a diverse suite of environments ranging from braided fluvial to glaciomarine (Labotka et al., 1980; Miller, 1985; Wright et al., 1976). An age of ca. 700 Ma is generally assumed, but this is only loosely bracketed between the 1.08 Ga diabasic sills in the underlying Crystal Spring Formation (Heamann and Grotzinger, 1992) and the base of the Cambrian, located 2 to 3 km stratigraphically above (Fig. 1). My database (29 mapped and measured sections) integrated with previous work (Harding, 1987; Labotka et al., 1980; Miller, 1985; Swanson, 1982) permits refining the age constraints and tectonostratigraphic evolution of the Kingston Peak Formation.

PROPOSED KINGSTON PEAK TECTONOSTRATIGRAPHIC FRAMEWORK

The marked facies changes exhibited by the Kingston Peak rocks across the Death Valley

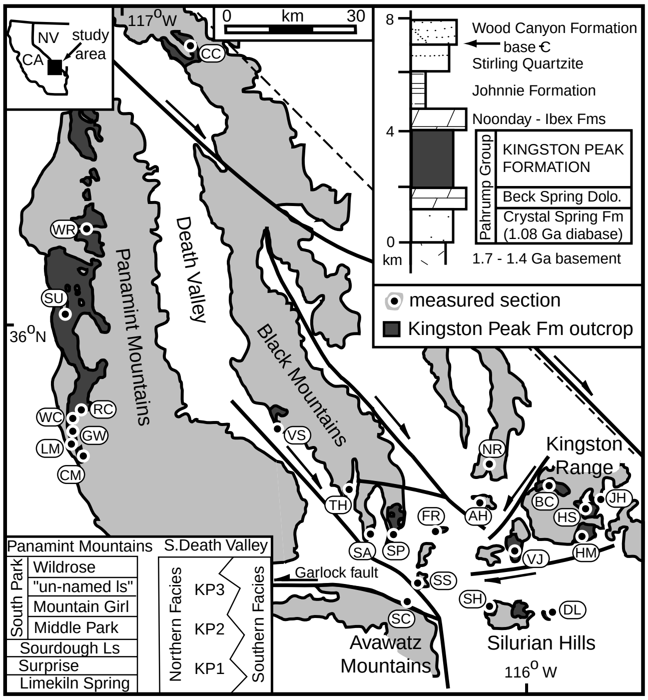

Figure 1. Kingston Peak Formation outcrop belt, Death Valley region; Neoproterozoic succession is upper right and Kingston Peak terminology is lower left. AH—Alexander Hills; BC—Beck Canyon; CC—Chloride Cliff; CM—Crescent Mine; DL—Dog-leg Wash; FR—Fatzinger Ridge; GW—Goler Wash; HM—Horse Thief Mine; HS—Horse Thief Spring; JH—Jupiter Hill; LM—Lotus Mine; NR—southern Nopah Range; RC—Redlands Canyon; SA—Saratoga Hills; SC—Sheep Creek; SH—Silurian Hills; SP—Saddle Peak Hills; SS—Salt Spring Hills; SU—Surprise Canyon; TH—Talc Hills; VJ—Valjean Hills; VS—Virgin Spring Wash; WC—Woodlands Canyon; WR—Wildrose Canyon. Note that several sections are too close to plot individually at this scale.

region have hindered construction of a unified stratigraphic framework. In the Panamint Range, the Kingston Peak Formation consists of a variably thick lower succession of coarse siliciclastic and diamictite deposits (the Limekiln Spring and Surprise Members) overlain by a heterolithic succession, including a patchily developed diamictite (Sourdough Limestone–South Park Member). In the Silurian Hills (SH, Fig. 1), it is mostly basement-clast bearing diamictite and turbidites (Southern facies of Troxel, 1967), whereas in the southern Black Mountains–Kingston Range area it consists of a lower mudstone, a middle diamictite, and an upper fanglomerate-turbidite, termed KP1, KP2, and KP3, respectively (Northern facies of Troxel, 1966). However, KP1 is genetically part of the Beck Spring Dolomite depositional cycle and thus KP2 marks the actual initiation of Kingston Peak deposition (Prave, 1994).

The lower Kingston Peak succession (Limekiln Spring–Surprise Members) in the Panamint Range and Northern facies succession in the southern Black Mountains–Kingston Range areas consist of nearly identical lithologies; the only difference is that the rocks in the Panamint Range are amphibolite grade. Both successions are floored by unconformities and are typified by carbonate-clast dominated diamictites, olistostromes containing enormous blocks and/or lenses of dolostone and older Crystal Spring diabase, and irregular mafic igneous bodies. Both also display unequivocal evidence for syndepositional extensional tectonism, i.e., buried normal faults, abrupt thickness and facies changes, and mid-oceanic ridge basalt (MORB) type volcanic rocks (Lanphere et al., 1964; Troxel, 1966; Labotka et al., 1980; Hammond, 1983; Miller, 1985). Taken together, and as argued by Miller (1983), these are compelling reasons to infer that both successions were deposited coevally during a major episode of lithospheric extension.

A younger extensional deformation episode can be similarly documented. In Goler Wash (GW, Figs. 1 and 2, A and B), the base of the youngest Kingston Peak unit, the Wildrose Diamictite, defines an angular unconformity that seals a Precambrian normal fault. The base of the Wildrose Diamictite bevels across older Kingston Peak units (including an olistostrome) and the fault to rest depositionally on basement gneiss in the area of the Lotus Mine (LM, Fig. 2, A and B). In places, the fault was active during initial Wildrose Diamictite deposition (lower Wildrose rocks are faulted against Limekiln Spring–Surprise rocks), but the fault is sealed by upper Wildrose units and the base of the Noonday Dolomite. Elsewhere in Death Valley, the Noonday Dolomite also seals normal faults (Wright et al., 1976). This confirms that a second episode of extensional deformation occurred at least as late as the initiation of Wildrose Diamictite deposition, but that it had mostly ceased by the time of early Noonday Dolomite deposition. Thus, the Kingston Peak Formation contains evidence for two temporally discrete episodes of extensional tectonism.

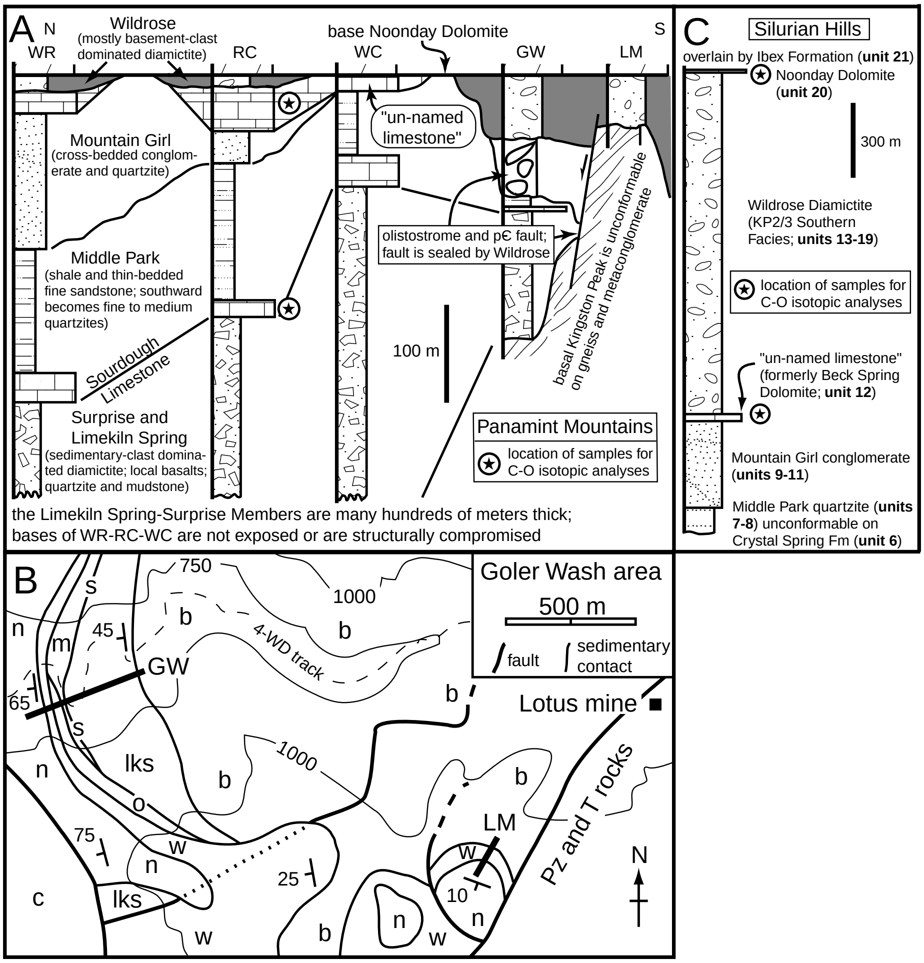

Figure 2. A: Stratigraphic cross section of upper Kingston Peak Formation north-south through Panamint Mountains (see Fig. 1 for locations and abbreviations). B: Simplified geologic map of Goler Wash area; note Precambrian fault that trends southwest-northeast through central part of map. Contours are in meters. Units: b—basement; c—Crystal Spring Formation; lks—Limekiln Spring and Surprise Members; m—Middle Park quartzite; n—Noonday Dolomite; o—olistostrome; s—Sourdough Limestone; w—Wildrose Diamictite. C: Silurian Hills section with proposed Kingston Peak member correlations; bold numbers are stratigraphic units of Kupfer (1960).

What occurred between these two episodes? In the Panamint Range, the Surprise Diamictite is sharply overlain by black, finely laminated carbonates of the Sourdough Limestone that pass gradationally upward into pelites and quartzites of the Middle Park quartzite, which are in turn sharply overlain by Mountain Girl conglomerate, an “un-named limestone” (a name adapted from Harding’s [1987] “un-named marble” in Wildrose Canyon), and the basement-clast–bearing Wildrose Diamictite. About 100 km to the southeast, the Pahrump Group in the Silurian Hills and adjacent areas (SH, DL, SS, SC, Fig. 1) is dominantly siliciclastic and the Kingston Peak Formation consists mostly of Southern facies rocks. Correlation of this succession to Pahrump exposures elsewhere has long vexed geologists studying Death Valley. My reinterpretation of the Silurian Hills stratigraphy (corroborated by C isotope data; see following) indicates that the post–Crystal Spring Formation there can be correlated unit by unit to the Middle Park–Wildrose succession in the Panamint Range (Fig. 2C). The sole exception (allowing for thickness differences) is that in the Silurian Hills the base of the Middle Park quartzite is an unconformity (it rests on Crystal Spring rocks) that must pass into a correlative conformity in the Panamint Range. These correlations imply that the limestone previously interpreted as Beck Spring Dolomite in the Silurian Hills (Kupfer, 1960) is actually the “un-named limestone” of the South Park Member, and that the Southern facies of Troxel (1967) is wholly equivalent to the Wildrose Diamictite (Fig. 2C). This correlation agrees with Miller’s (1983) contention that the Surprise Member and Northern facies rocks are correlative and older than the Wildrose Diamictite and Southern facies rocks. Others have contested this correlation because of the observation that, in certain localities south and east of Death Valley, Southern and

Northern facies rocks occur in close proximity and thus were assumed to be coeval. I have carefully reexamined many of those localities. My observations indicate that the lateral juxtaposition of Northern and Southern facies rocks is due to erosional incision and not coeval interfingering. For example, in the Alexander Hills (Fig. 3) Southern facies rocks (Wildrose Diamictite equivalent) occur in an incised valley that erodes into and sharply truncates Northern facies units. Thus, the Kingston Peak Formation contains two temporally distinct diamictite intervals separated by a stratigraphic succession (most of the South Park Member) marked by a uniform, consistent facies character. This implies a period of relative tectonic quiescence between two pronounced episodes of extensional deformation.

One other stratigraphic issue needs to be resolved. On the basis of exposures in Surprise Canyon (SU, Fig. 1), Miller (1987) concluded that the "un-named limestone" and lower Noonday Dolomite were facies equivalents. However, my mapping in the southern Panamint Range and reevaluation of the Surprise Canyon mapping has documented that the base of the Noonday Dolomite cuts irregularly downsection to rest variably on Wildrose Diamictite or "un-named limestone" or older units (Fig. 2A). This indicates that the lower Noonday Dolomite (a tan, mostly microbial-laminated dolo[calc]micrite) and "un-named limestone" (a gray, traction-bedded, sandy, oolitic grainstone-wackestone) are genetically unrelated. Consequently, as elsewhere in Death Valley, the Kingston Peak Formation–Noonday Dolomite formation contact is unconformable.

Thus, regional unconformities (and correlative conformities) can be used to define three Kingston Peak Formation tectonostratigraphic units (Fig. 4A): TU1—Limekiln Spring–Surprise Diamictite–Northern facies (KP2-3 only)–Sourdough Limestone; TU2—Middle Park quartzite–"un-named limestone"; and TU3—Wildrose Diamictite–Southern facies.

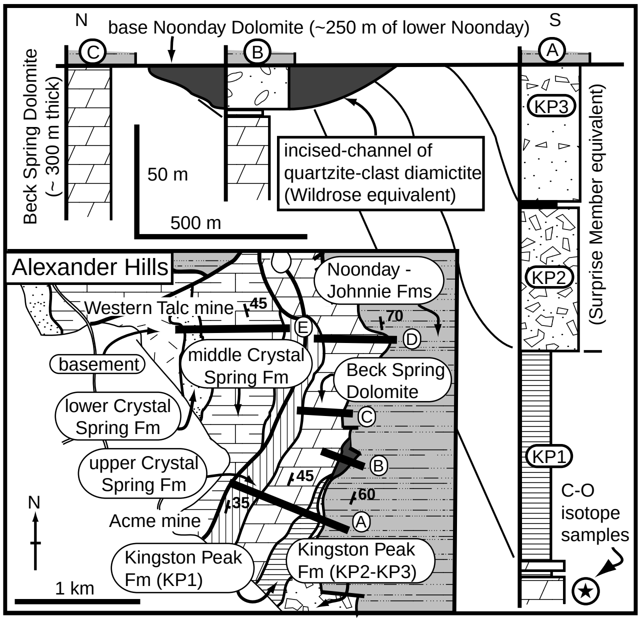

Figure 3. Stratigraphic cross section (measured sections A–C) and map (modified from Wright, 1954) of Alexander Hills (AH; see Fig. 1). Note how Wildrose-equivalent diamictite erosionally truncates underlying Kingston Peak units KP1 and KP2.

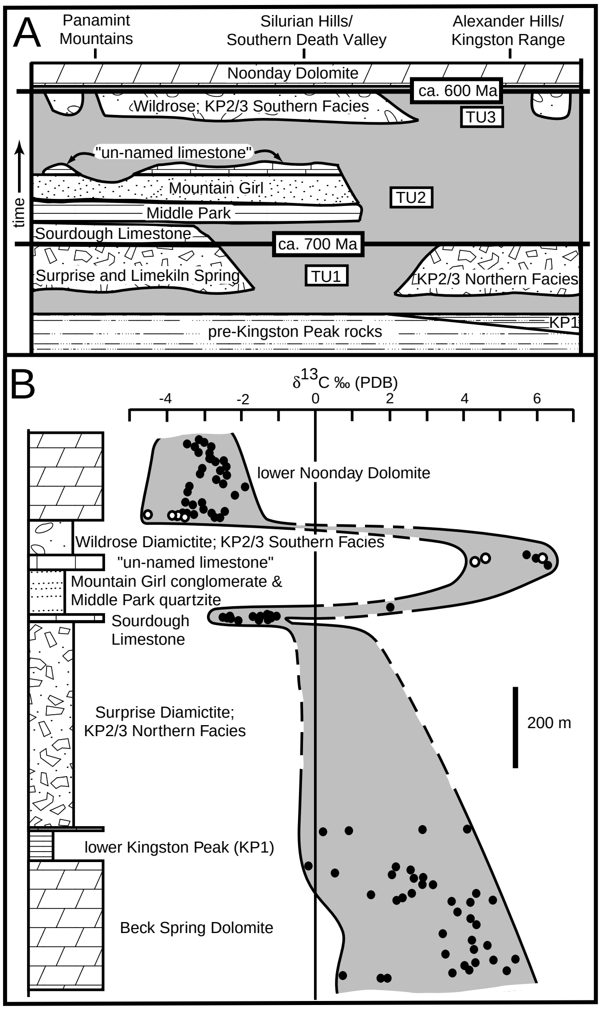

Figure 4. A: Wheeler diagram cartoon for Kingston Peak tectonostratigraphic units (TU 1–TU 3); absolute durations of units and hiatal surfaces are not known precisely and are shown schematically. Absolute ages are for Sturtian and Varangian glacials. B: $\delta^{13}C$ trends for Neoproterozoic carbonate units in Death Valley region. Closed circles are for sample sites shown in Figures 2 and 3; Noonday Dolomite samples are from southern Nopah Range section (NR; see Fig. 1). Open circles refer to Silurian Hills data (Fig. 2C). PDB is Peedee belemnite.

CHEMOSTRATIGRAPHIC DATA

The C isotope stratigraphy has become a widely applied methodology for establishing chronostratigraphy in otherwise unfossiliferous or radiometrically undatable Precambrian rocks (e.g., Kaufman et al., 1997). The C isotope data (obtained and analyzed following standard techniques, e.g., Kaufman et al., 1991) have proven critical in establishing a unified Kingston Peak stratigraphy and its correlation to other Neoproterozoic glacial deposits. Heavy $\delta^{13}C$ trends (Fig. 4B) mark the Beck Spring Dolomite and KP1 limestones with values to 5.16‰ (most are >3.0‰). Heavy values also characterize the "un-named limestone" and Silurian Hills limestone and range between 4.33 and 6.27‰ (such heavy values are rare and this strongly supports their correlation). In contrast, the Sourdough Limestone and Noonday Dolomite, which immediately overlie glaciogenic diamictites, record marked negative shifts between –1.11 and –2.56‰ and –1.88 and –4.86‰, respectively. The Sourdough Limestone trend shifts toward positive values (2.15‰) within 15 m of the base, but the Noonday Dolomite trend remains negative for more than 200 m. These trends and the facies characteristics of the Sourdough Limestone and Noonday Dolomite rocks match those of Sturtian and Varangian age cap carbonates. Sturtian cap carbonates are dark colored finely laminated dolo(lime)stones with $\delta^{13}C$ values lightest near the base (to –4‰), and become heavier typically over 1–20 m. In contrast, Varangian cap carbonates are cream-colored laminated dolo(calc)micrites with light $\delta^{13}C$ values (to –6‰) for many tens to several hundreds of meters above the base (Kennedy et al., 1998; Kaufman et al., 1997). Consequently, I interpret the Sourdough Limestone and Noonday Dolomite as the ca. 700 Ma Sturtian and ca. 600 Ma Varangian caps, respectively (ages from Young, 1995).

TECTONIC IMPLICATIONS, SPECULATIONS, AND CONCLUSIONS

Unit TU1 contains compelling evidence for syndepositional extensional tectonism that, given the linkage of this succession to the Sturtian glacial, occurred ca. 700 Ma. Similar evidence in TU3 rocks and their link to the Varangian glacial indicates that a second phase of extensional tectonism occurred ca. 600 Ma. The intervening ~100 m.y. is marked by TU2, a relatively thin succession that displays a uniform, consistent facies character and thus provides no evidence to infer deposition under the influence of extensional tectonics. Its absence throughout much of the Death Valley area mostly reflects erosional removal (of an unknown amount), rather than nondeposition, beneath the basal unconformities of the Wildrose Diamictite and Noonday Dolomite. These observations, coupled with the fact that much of TU2 was derived from a western provenance (Swanson, 1982), suggest that during the ca. 700 Ma extensional episode the Death Valley region was cratonward of the main area of uplift (rift-flank uplift?) and lithospheric thinning. This implies that TU2 would have formed over lithosphere undergoing minimal thermal subsidence, hence the lack of a well-developed postrift stratigraphy following the ca. 700 Ma extensional event. The later erosional beveling of TU2 rocks indicates that much of the Death Valley area east of the Panamint Range must have straddled the region of doming associated with the ca. 600 Ma event; thus the base of TU3 defines a breakup unconformity. The widespread development of the post-Noonday Dolomite succession across the southwestern Great Basin can therefore be attributed to subsequent thermal-mechanical subsidence along thinned lithosphere during rift to drift tectonics.

These data and interpretations show that the conundrum between field geologists, whose observations imply an early rift event, and tectonic-subsidence modelers, whose results require a later rift event, is largely unfounded: apparently both are correct. The challenge now is to devise geologically compatible plate configurations for Laurentia's southwestern margin that account for two discrete Neoproterozoic rifting events separated by 100 m.y. or more.

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REFERENCES CITED

Bond, G. C., 1997, New constraints on Rodinia breakup ages from revisited tectonic subsidence curves: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. 280.

Bond, G. C., and Kominz, M. A., 1984, Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains: Implications for subsidence mechanisms, age of breakup, and crustal thinning: Geological Society of America Bulletin, v. 95, p. 155–173.

Bond, G. C., Christie-Blick, N., Kominz, M. A., and Devlin, W. J., 1985, An Early Cambrian rift to post-rift transition in the Cordillera of western North America: Nature, v. 316, p. 742–745.

Dalziel, I. A. D., 1997, Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation: Geological Society of America Bulletin, v. 109, p. 16–42.

Hammond, J. G., 1983, Late Precambrian diabase intrusions in the southern Death Valley region, California: Their petrology, geochemistry, and tectonic implications [Ph.D. thesis]: Los Angeles, University of Southern California, 281 p.

Harding, M. B., 1987, The geology of the Wildrose Peak area, Panamint Mountains, California [M.S. thesis]: Laramie, University of Wyoming, 207 p.

Heaman, L. M., and Grotzinger, J. P., 1992, 1.08 Ga diabase sills in the Pahrump Group, California: Implications for development of the Cordilleran miogeocline: Geology, v. 20, p. 637–640.

Kaufman, A. J., Hayes, J. M., Knoll, A. H., and Germs, G. J. B., 1991, Isotopic composition of carbonates and organic carbon from upper Proterozoic successions in Namibia: Stratigraphic variation and the effects of diagenesis and metamorphism: Precambrian Research, v. 49, p. 301–327.

Kaufman, A. J., Knoll, A. H., and Narbonne, G. M., 1997, Isotopes, ice ages, and terminal Proterozoic earth history: National Academy of Science Proceedings, v. 94, p. 6600–6605.

Kennedy, M. J., Runnegar, B., Prave, A. R., Hoffmann, K. H., and Arthur, M. A., 1999, Two or four Neoproterozoic glaciations?: Geology, v. 26, p. 1059–1063.

Kupfer, D. L., 1960, Thrust faulting and chaos structure, Silurian Hills, San Bernardino County, California: Geological Society of America Bulletin, v. 71, p. 181–214.

Labotka, T. C., Albee, A. L., Lanphere, M. A., and McDowell, S. C., 1980, Stratigraphy, structure and metamorphism in the central Panamint Mountains (Telescope Peak quadrangle), Death Valley area, California: Geological Society of America Bulletin, v. 91, part II, p. 843–933.

Lanphere, M. A., Wasserburg, G. J. F., Albee, A. L., and Tilton, G. R., 1964, Redistribution of strontium and rubidium isotopes during metamorphism, World Beater complex, Panamint Range, California, *in* Craig, H., et al., eds., Isotopic and cosmic chemistry: Amsterdam, North Holland Publishing, p. 269–320.

Levy, M., and Christie-Blick, N., 1991, Tectonic subsidence of the early Paleozoic passive continental margin in eastern California and southern Nevada: Geological Society of America Bulletin, v. 103, p. 1590–1606.

Miller, J. M. G., 1983, Stratigraphy and sedimentology of the Upper Proterozoic Kingston Peak Formation, Panamint Range, California [Ph.D. thesis]: Santa Barbara, University of California, 355 p.

Miller, J. M. G., 1985, Glacial and syntectonic sedimentation: The Upper Proterozoic Kingston Peak Formation, southern Panamint Range, eastern California: Geological Society of America Bulletin, v. 96, p. 1537–1553.

Miller, J. M. G., 1987, Paleotectonic and stratigraphic implications of the Kingston Peak–Noonday contact in the Panamint Range, eastern California: Journal of Geology, v. 95, p. 75–85.

Prave, A. R., 1994, The Pahrump Group: Alternative speculations on the Neoproterozoic geodynamic development of the Death Valley region: Geological Society of America Abstracts with Programs, v. 26, no. 2, p. 82.

Ross, G. M., 1991, Tectonic setting of the Windermere Supergroup revisited: Geology, v. 19, p. 1125–1128.

Stewart, J. H., 1976, Late Precambrian evolution of North America: Plate tectonics implication: Geology, v. 4, p. 11–15.

Swanson, S. C., 1982, Sedimentology and provenance of the South Park Member of the Kingston Peak Formation, Panamint Range, California [M.S. thesis]: Los Angeles, University of California, 161 p.

Troxel, B. W., 1966, Sedimentary features of the later Precambrian Kingston Peak Formation, Death Valley, California: Geological Society of America Special Paper 101, 341 p.

Troxel, B. W., 1967, Sedimentary rocks of late Precambrian age in the southern Salt Spring Hills, southeastern Death Valley, California: California Division of Mines and Geology Special Report 92, p. 33–41.

Wright, L. A., 1954, Geology of the Alexander Hills area, Inyo and San Bernardino Counties, California: California Division of Mines and Geology Bulletin 170, map sheet 17, scale 1.

Wright, L. A., Troxel, B. W., Williams, E. G., Roberts, M. T., and Diehl, P. E., 1976, Precambrian sedimentary environments of the Death valley region, eastern California: California Division of Mines and Geology Special Report 106, p. 7–15.

Young, G. M., 1995, Are Neoproterozoic glacial deposits preserved on the margins of Laurentia related to fragmentation of two supercontinents?: Geology, v. 23, p. 153–156.

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