Chapter 40

The Kingston Peak Formation in the eastern Death Valley region

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Abstract: The late Neoproterozoic Kingston Peak Formation (Fm.) is a several-kilometre-thick sedimentary succession primarily influenced by syndepositional tectonism and located in the region around Death Valley, California (Fig. 40.1). Its distribution is divisible into an eastern facies assemblage, the subject of this paper, and a western facies assemblage covered in a separate chapter. The diamictite-bearing Kingston Peak Fm. is bounded by the underlying shallow platform carbonates of the Beck Spring Fm. and overlain by the Noonday Dolomite. There is an absence of direct palaeolatitude or radiometric age constraints and any correlation is based on broad similarities with other coarse-grained strata (diamictite) located in a northward trending belt along the Cordilleran miogeocline. The overlying Noonday Dolomite has been interpreted to be a late Cryogenian 'cap carbonate' and shares a set of unique facies associations and isotopic and lithological characteristics with other late Neoproterozoic post-glacial carbonate intervals in Namibia, Canada, Australia and Brazil. Research to date has focused on understanding local basin evolution, glacial sedimentology, correlation between the eastern and western facies assemblages and initiation and development of the North American Cordillera. The intimate association of tectonic and glacial facies with rapid local thickness and facies changes corresponding with syn-sedimentary faulting is the most distinctive stratigraphic characteristic of the Kingston Peak Fm. The complex local stratigraphy complicates correlation both within the Death Valley region as well as globally, and pending absolute age dates, does not fit easily with conventional Cryogenian Period glacial models identifying two or more discrete ice ages.

The Kingston Peak Fm. (KPF) is the uppermost of the three formations in the Pahrump Group (Hewett 1940) (Fig. 40.1), which comprises the oldest sedimentary rocks preserved in the region. It crops out throughout the Death Valley region of southeastern California, where active extensional tectonism associated with the Basin and Range province along with an arid climate allow clear lateral stratigraphic and facies relations to be observed. The mixed carbonate–siliciclastic sediments of the Crystal Spring Fm. and overlying shallow marine carbonate of the Beck Spring Dolomite comprise the basal and middle formations, respectively, of the Pahrump Group. The KPF is overlain by the Noonday dolomite (Fig. 40.1)

Description of the KPF is complicated by its division into a distinctive western facies assemblage (Petterson *et al.* 2011; western-KPF) along the western boundary of Death Valley in the Panamint Range and a distinctive eastern facies assemblage (this chapter; eastern-KPF) that itself is subdivided into northern and southern facies (Fig. 40.1). The KPF also crops out in the Funeral Mountains further north (Miller 1983) but has undergone amphibolite-grade metamorphism (Mattinson *et al.* 2007) and is not well-studied. Eastern and western facies assemblages of the KPF are dominated by similar coarse-grained siliciclastic rocks, but lithostratigraphic correlation is complicated by lateral facies changes within each facies assemblage (Miller 1983), an overall difference in the appearance of specific facies between both regions and the presence in each region of distinctive carbonate intervals bounded by dissimilar facies.

The eastern facies assemblage (also referred to as southeastern KPF in the literature) crops out in the southern Black Mountains and in a number of hills and ranges SE of the Black Mountains, primarily in the Kingston Range (Fig. 40.1). More specifically, it crops out extensively in a readily accessible 30-km-long belt along the northern and eastern flanks of the Kingston Range (Hewett 1940) and is superbly exposed in a panel extending from the Silver Rule Mine (35°48′17″N, 115°56′39″W, #6 in Fig. 40.1) to Beck Canyon Divide (35°48′19″N, 115°55′31″W, #7 in Fig. 40.1). The northern Kingston Range is the location of three characteristic KPF sections published in Hewett (1956; Fig. 40.1). It is the best location to examine the eastern-KPF because of a relative lack of metamorphism, laterally persistent outcrops and visibility of rapid lateral facies changes.

Much of the interval of coarse-grained sediments comprising the KPF was first described in detail from the Panamint Range and informally named in the Telescope group by Murphy (1930, 1932) as the Surprise Fm., Sourdough Limestone, Middle Park Fm. and Wildrose Fm., from bottom to top respectively. These names have been retained but subsequently assigned to formal member status (Johnson 1957; Carlisle *et al.* 1980; Labotka *et al.* 1980) within Hewett's (1940) Kingston Peak Fm. (Fig. 40.1). Noble (1934, 1941) described the eastern-KPF and likened it to the 'Algonkian' series in the Grand Canyon, suggesting a correlation to Murphy's (1932) Telescope group (later the KPF) in the Panamint Range. Hazzard (1939) interpreted the KPF to be glaciogenic based on the presence of striated clasts at the Gunsight Mine in the uppermost KPF.

From 1950 to the mid-1980s, relevant publications focused on the stratigraphy, sedimentology, palaeogeography and source regions for the different facies of the KPF (Wright 1952, 1968; Wright & Troxel 1966; Troxel 1967, 1982*b*; Wright *et al.* 1976, 1978, 1984). From the early 1980s onwards, publications primarily addressed the glacial and tectonic features in the eastern and western facies assemblages (Miller 1982, 1983, 1985, 1987; Christie-Blick & Levy 1989; Link *et al.* 1993), providing interpretations for the role of glaciation and extension in the deposition of the KPF as well as using the succession to help interpret the evolution of the developing passive margin of the western Cordillera (Levy & Christie-Blick 1989, 1991; Fedo & Cooper 2001). Prave (1999) proposed a chemo- and tectono-stratigraphic correlation for the eastern and western facies assemblages of the KPF, suggesting the entire formation fit into a 'Snowball Earth' model (Hoffman *et al.* 1998) with a stratigraphic record of two discrete ice ages. Most recently, Mrofka (2010) discussed the usefulness of carbonate intervals as timelines and the important relationship between syndepositional tectonism and preservation of the climate record in both the eastern- and western-KPF.

Structural framework

The KPF is concentrated in extensional basins, products of syndepositional tectonism (Mrofka 2010) likely associated with

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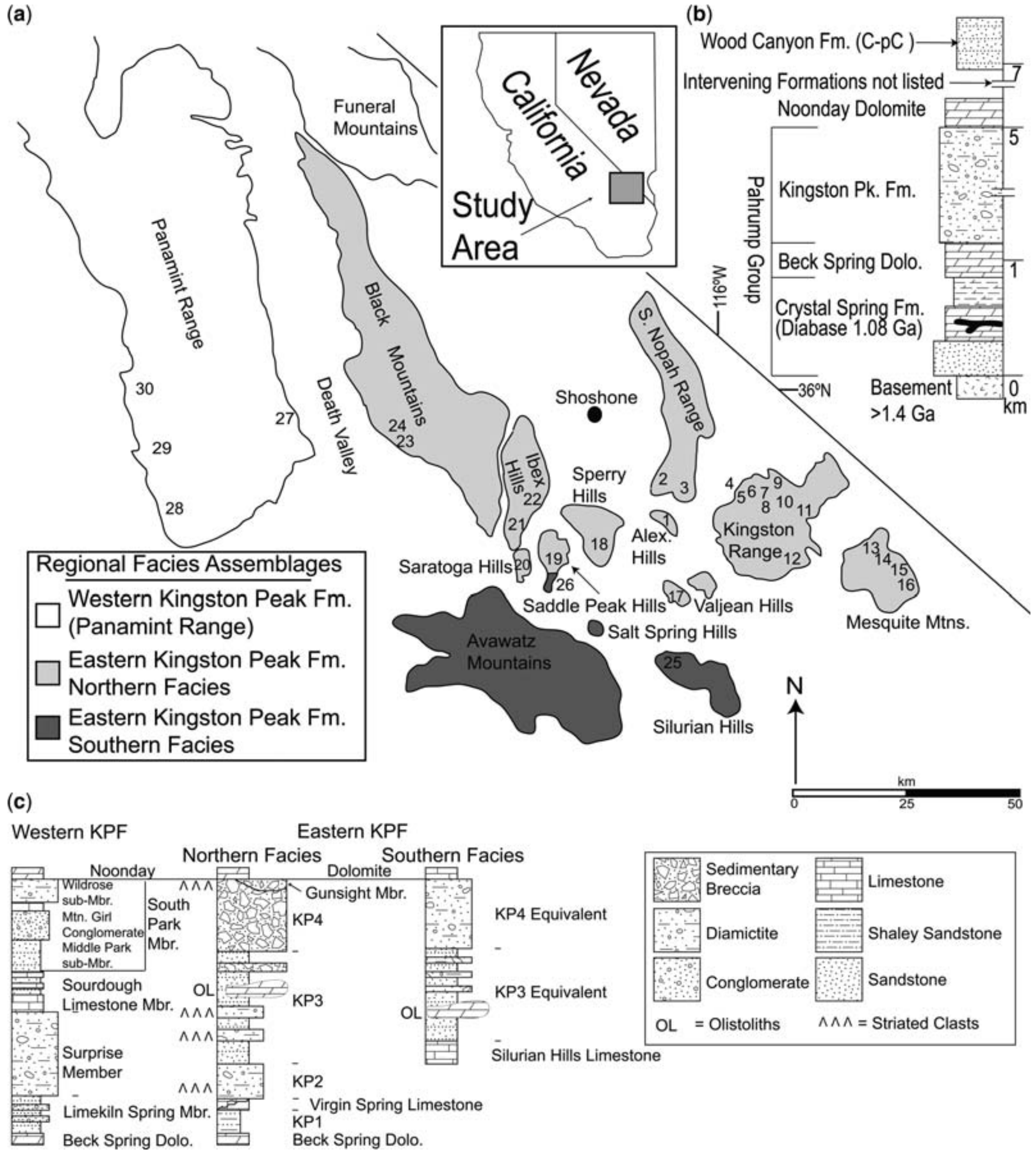

Fig. 40.1. (**a**) Map showing regional distribution of the western (white; see Petterson *et al.* 2011 for more detail) and eastern (northern, light-shaded; southern, dark-shaded) facies assemblages of the Kingston Peak Fm. Numbers represent measured sections used for this study: 1, Alexander Hills; 2, Gunsight Mine; 3, War Eagle Mine; 4, Beck Canyon West; 5, Crystal Spring; 6, Silver Rule Mine; 7, Beck Canyon Divide; 8, Horsethief Spring; 9, Kingston North; 10, Jupiter Mine; 11, Snow White Mine; 12, Horsethief Mine; 13, Mesquite North; 14, Mesquite South; 15, Mesquite Small Block; 16, Winters Pass; 17, Southern Valjean Hills; 18, Sperry Hills; 19, Saddle Peak Hills; 20, Saratoga Hills; 21, Ibex Hills; 22, Eclipse Mine; 23, Virgin Spring Wash south; 24, Virgin Spring Wash north; 25, Silurian Hills; 26, southern Saddle Peak Hills; 27, Galena Canyon; 28, Goler Wash; 29, Wood Canyon; 30, Sourdough Canyon. Type sections from Hewett (1956) are #7, #8 and 3 km south of #8. (**b**) Generalized stratigraphy of the Pahrump Group showing predominance of coarse-grained facies in the Kingston Peak Fm. relative to the bounding carbonate strata. (**c**) Schematic stratigraphic logs comparing the different facies assemblages of the Kingston Peak Fm. across the Death Valley region.

rifting along the western margin of North America between 850 and 600 Ma (Stewart 1972; Christie-Blick & Levy 1989). During extension and uplift along normal faults, resulting basins were filled with sediments derived from successively older stratigraphic levels of the underlying Pahrump Group (Wright *et al.* 1976, 1992; Burchfiel *et al.* 1992). Evidence for extension includes a preponderance of coarse-grained sediments including kilometre-scale olistoliths (Miller 1985), syndepositional normal faults in the Kingston Range (Mrofka 2010), the southern Nopah Range (Wright *et al.* 1976, 1978) and the Panamint Range (Prave 1999) and tholeiitic (Hammond 1983) pillow lavas in the Panamint Range (Miller 1985). Vertical offsets on the faults are >400 m in the Kingston Range at Jupiter Hills (Fig. 40.1), as demonstrated by removal of the entire Beck Spring Dolomite on the footwall side of faults, and possibly the removel of as much as 3 km of rock elsewhere (Burchfiel *et al.* 1992).

Sedimentation in the Death Valley region was relatively continuous throughout the Palaeozoic (Abolins *et al.* 2000) but underwent compressional shortening in the Permian (Snow 1992) and again during the Mesozoic (Levy & Christie-Blick 1989), with accompanying metamorphism in the Panamint Range (western-KPF) (Labotka *et al.* 1980). In the Kingston Range, north-northeastwards tilting strata of the eastern-KPF are generally offset along north–south trending normal faults and, in the southern Kingston Range, a detachment system occurs related to Cenozoic extension of the Basin and Range province (Davis *et al.* 1993). Levy & Christie-Blick (1989) estimated *c.* 150% extension to the original pre-Mesozoic basin after Mesozoic compression and later Cenozoic extension. Estimates for Cenozoic extension range from *c.* 50–500% (Wright & Troxel 1967; Wernicke *et al.* 1988; Miller 1991), with higher estimates recently called into question by the findings of Renik *et al.* (2008). At its western boundary, in the southern Black Mountains, the eastern-KPF has undergone significant structural complication (Noble 1941; Troxel & Wright 1987; Miller 1991).

Stratigraphy

Underlying Pahrump Group

The lower and middle formations in the Pahrump Group (Fig. 40.1b) record a transition from mixed carbonate–siliciclastic marine and fluvial facies of the Crystal Spring Fm. (Roberts 1974) to the Beck Spring Dolomite, comprised of shallow-water carbonates in the north and mixed carbonate–siliciclastic fluvial–tidal deposits south of the central Saddle Peak Hills (Marian & Osborne 1992). In the Kingston Range, Marion & Osborne (1992) divided the Beck Spring Dolomite into (i) a lower, laminated, cherty member, (ii) a laminated member with angular intraclasts and columnar stromatolites, (iii) a relatively thinner oolitic–pisolitic member and (iv) a partially silicified upper member with abundant chert, shale lenses and stromatolites.

Kingston Peak Fm.: Eastern Facies Assemblage

The coarse-grained siliciclastic eastern-KPF is separated into a northern and southern facies based primarily on the distinct lithology of clasts in diamictite from each area (Troxel 1967). The northern facies of the eastern-KPF is the focus of this contribution and is informally separated into the KP1 through KP4 members (Wright 1974) (Fig. 40.1a, c). The southern facies is limited in outcrop relative to the northern facies. Other prominent units within the KPF include (i) a black laminated karstic limestone unit (Virgin Spring Limestone) that locally separates the KP1 and KP2 members, (ii) a discontinuous dolostone bed in the lower half of the KP3 Member in the Kingston Range (Corsetti & Kaufman 2003) and (iii) lenses of diamictite that often overlie the KP4 Member (referred to informally as the Gunsight Member).

The basal KP1 and Virgin Spring Limestone of the northern facies are separated from the glaciogenic units of KP2 through KP4 by a regional unconformity (Fig. 40.1c). Based on stratigraphic and sedimentary characteristics, these two basal units should constitute separate formations, but this has only come to light recently with the identification of the regional unconformity (Mrofka 2010). The current stratigraphic scheme (Fig. 40.1c) and member names are retained here until formal stratigraphic nomenclature is published elsewhere.

Noonday Dolomite

The Noonday Dolomite overlying the eastern-KPF is divided into a lower, cream-coloured, laminated, microbial, dolomite member and an upper, laminated, silty, dolomite member (Wright *et al.* 1978). The laminations at the base several metres of the lower member are parallel and horizontal, transitioning upwards to arching laminations that define larger-scale microbial mounds with synoptic relief of up to 200 m (Williams *et al.* 1974). Alternatively, Summa (1993) suggested apparent mound 'topography' was due to an intra-formational erosion surface. The lower member contains distinctive vertical tubes possibly related to vertical transport of fluids (Cloud *et al.* 1974; Kennedy *et al.* 2001*b*) or microbial processes (Corsetti & Grotzinger 2005) and centimetre- to decimetre-scale pockets of sparry cement (Cloud *et al.* 1974; Williams *et al.* 1974). In the east, the Noonday Dolomite transitions southwards to a siliciclastic-rich facies (Ibex Fm.), which includes an arkosic siltstone member, a shaley-limestone member and a quartz-dolomite member (Williams *et al.* 1974).

Glaciogenic deposits and associated strata

Glaciogenic strata occur in the KP2–KP4 members of the Kingston Peak Fm. as well as in the southern facies assemblage (Fig. 40.1c). Deposition of the basal KP1 Member and overlying Virgin Spring limestone was not influenced by glacial processes and both are therefore described subsequently within this section as associated strata.

KP2 Member, northern facies: regional unconformity and diamictite deposition

The KP2 Member comprises a regionally extensive blanket of massive- to diffusely-bedded cobble-boulder diamictite, which varies from 10 to 250 m in thickness. It sharply overlies a regionally extensive unconformity (Mrofka 2010), which defines the top of the underlying KP1 Member or Virgin Spring limestone and contains striated and faceted clasts. Clasts within the diamictite are derived from the underlying Pahrump Group or basement and the matrix is composed of coarse angular quartz sand and illite (mica) or chlorite. Basal diamictite commonly contains black limestone clasts and a carbonate-rich matrix likely derived from the underlying Virgin Spring limestone. In the Saratoga Hills, southern Saddle Peak Hills and Alexander Hills, the diamictite facies is interrupted by a 5–20 m interval of finer-grained facies, variably including siltstone and sandstone with parallel laminations, trough cross-bedding, steep bimodal cross-lamination and normally graded pebble conglomerates with sandy tops.

KP3 Member, northern facies: sandstone, breccia and conglomerate

The KP3 Member is 15–2000 m thick, consists of interbedded siltstone and sandstone, diamictite with striated clasts, normally graded conglomerate beds, kilometre-scale olistoliths and channel-filling sedimentary breccia. The lower KP3 Member is comprised primarily of siltstone and sandstone interbedded with minor diamictite and conglomerate. Pebble- to cobble-sized outsized clasts commonly float in sandstone beds that grade laterally to conglomerate or diamictite. Sedimentary structures include normally graded beds, convolute laminations and siltstone with intraclasts and flame structures. A 2–3-m-thick oncolitic dolostone in the Kingston Range (35°46′27″N, 115°52′59″W) is found near the top of the finer-grained lower KP3 Member and marks a coarsening-upwards transition to interbedded sandstone, normally graded conglomerate and diamictite. As with the KP2 Member, diamictite intervals commonly contain black limestone clasts in a black calcitic matrix. The middle to upper KP3 Member is characterized by metre- to kilometre-scale mega-clasts and olistoliths of the underlying Pahrump Group that form prominent ridges in the Kingston Range around 35°44′43″N, 115°51′5″W and 35°44′35″N, 115°50′22″W (Wright *et al.* 1976). Fe-rich (45% iron by weight) units at Sperry Wash (Abolins *et al.* 2000) are found near Tertiary-age faulting and volcanic intrusions.

KP4 Member, northern facies: sedimentary breccia and conglomerate

The KP4 Member gradationally overlies the KP3 Member and comprises 200–1300 m of conglomerate, sedimentary breccia and monomictic mega-breccia (Figs 40.1 & 40.2). Conglomerate and breccia beds are commonly normally graded and fill channels 1–2 m deep and 10–50 m wide. Mega-breccia is massive, dominated by up to metre-scale angular blocks of Beck Spring Dolomite and filling steeper and narrower channels than the graded breccia and conglomerate beds. In the Kingston Range, sedimentary breccia composed entirely of Beck Spring Dolomite was deposited adjacent to a syndepositional fault (35°47′22″N, 115°50′1″W, #10 in Fig. 40.1). Laterally, sedimentary breccia and conglomerate is interbedded with normally graded to massive sandstone beds with sharp planar lower bed contacts. In footwall sections, the KPF is composed entirely of a diamictite interval informally named the Gunsight Member (Troxel pers. comm.). Near the Jupiter Mine (35°47′28″N, 115°50′1″W, #10 in Fig. 40.1), the Gunsight Member includes channelized sandstone with mudcracks and ripples overlain by diamictite with striated clasts.

Glaciogenic deposits of the southern facies

Outcrops of the southern facies of the eastern-KPF (dark grey shading in Fig. 40.1) are limited to a *c.* 8-km-wide belt of quartzite,

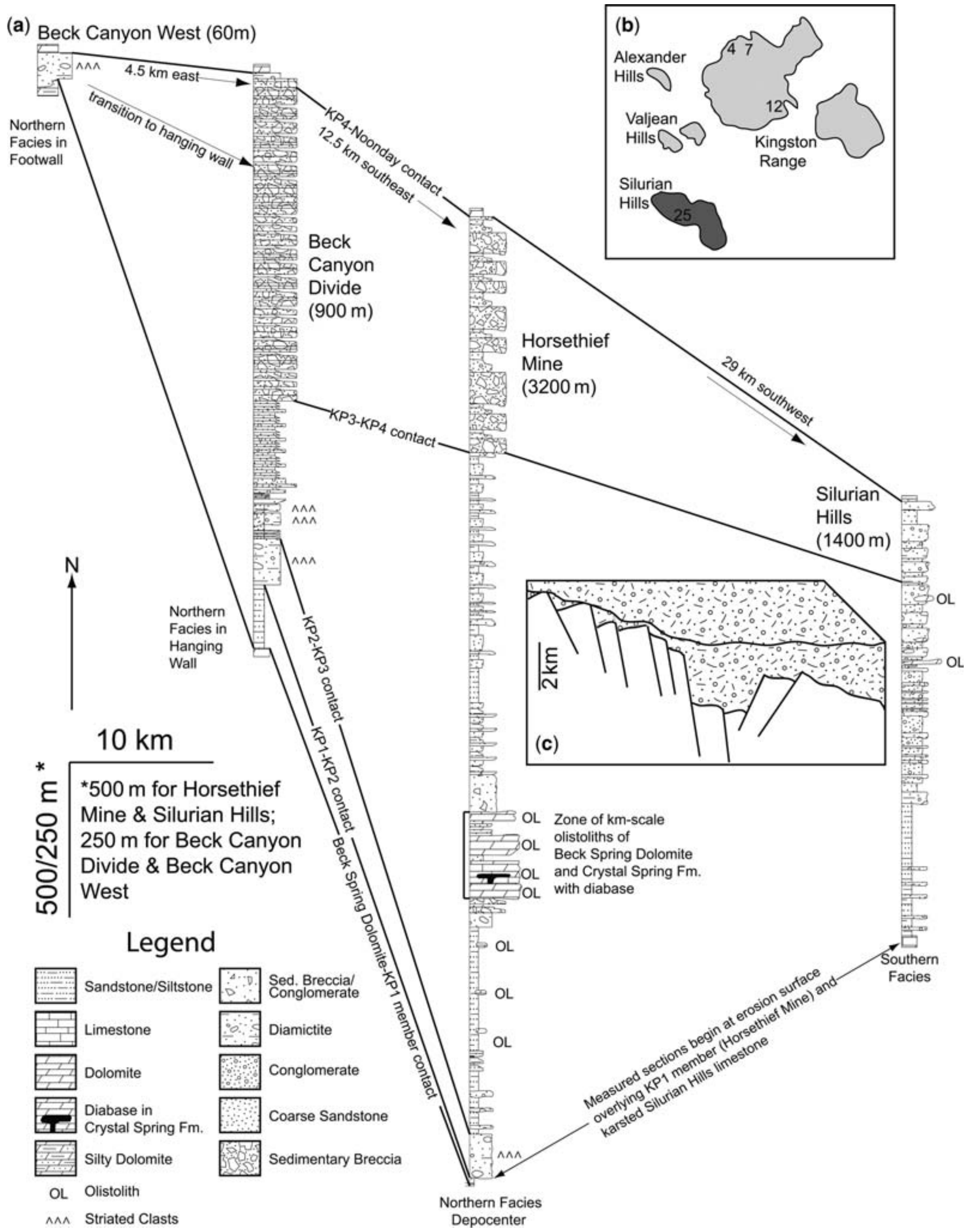

Fig. 40.2. (**a**) Cross-section of four measured sections showing footwall to hanging wall transition and relationship between northern and southern facies. Numbers next to section names represent approximate section thicknesses. Note: different vertical scales are used. Northern facies sections rest on the Beck Spring Dolomite, except at the War Eagle mine, where the Gunsight Member rests on the Crystal Spring Fm. Uppermost unit shown is the Noonday Dolomite. (**b**) Map showing location of measured sections: 4, Beck Canyon West; 7, Beck Canyon Divide; 12, Horsethief Mine; 25, Silurian Hills. (**c**) Schematic diagram showing typical extensional geometry of graben deposits thought to apply to the eastern-KPF (after Faerseth *et al.* 1997).

conglomerate and diamictite that crops out in the southern Saddle Peak Hills, the southern Salt Spring Hills and in the Silurian Hills. In the southern Salt Spring Hills, the southern facies is 1000 m thick and dominantly composed of quartzite with *c.* 75 m of basement clast-bearing diamictite capping the lower third of the section (Troxel 1967). In the Silurian Hills, the eastern-KPF is $>$2000 m thick (Kupfer 1960) and is floored by a dark parallel-laminated karsted limestone. Kupfer (1960) correlated this limestone to the Beck Spring Dolomite, but Prave (1999) correlated it to a discontinuous limestone below the Wildrose sub-Member in the western-KPF. Prave's (1999) correlation was based on similarities in $\delta^{13}C$ values and the appearance of a quartzite cobble conglomerate below both limestone intervals. The section above the limestone coarsens upwards and contains normally graded sandstone and conglomerate, diamictite and megaclasts (tens of metres scale).

Similarities between the northern and southern facies include karsted and laminated limestone facies overlain by sandstone beds, a coarsening-upwards trend above the karsted limestone intervals, and the presence of megaclasts. These similarities suggest the limestone in the Silurian Hills may alternatively be correlated to the Virgin Spring Limestone in the northern facies. Unlike northern facies diamictite, the diamictite in the southern facies is dominated by clasts of granite and gneiss (Troxel 1967). Troxel (1982*a*) suggested this diamictite is interbedded with the northern facies in the southern Saddle Peak Hills.

KP1 Member, northern facies: sandstone and siltstone

The non-glaciogenic KP1 Member is 1 to 180 m thick, composed of centimetre-scale beds of parallel laminated sandstone and siltstone and underlies a regional erosional unconformity. Sedimentary structures include low-angle cross-lamination, beds with scoured bases, rare massive sandstone beds with mudstone chips and a general coarsening and increase in carbonate cement upsection. In the southern Black Mountain (35°54′45″N, 116°38′50″W, #23 and 24 in Fig. 40.1), the KP1 Member varies in thickness by *c.* 30 m over a lateral distance of 100 m due to erosional truncation.

Virgin Spring limestone, northern facies

The Virgin Spring limestone (Tucker 1986) sharply overlies the KP1 Member, is erosionally truncated and karsted, dark, parallel-laminae, and is preserved in only three localities. The limestone is 17 m thick and best exposed in the Ibex Hills (35°45′18″N, 116°26′12″W, #21 in Fig. 40.1), but also crops out at Virgin Spring Wash and in the Saratoga Hills where it is <4 m thick and gradually truncated to the south (Fig. 40.1). Tucker (1986) described the Virgin Spring limestone as comprising of centimetre- to decimetre-scale beds of parallel laminated limestone interbedded with <1-mm-thick sandstone laminae with scoured bases and occasional normal grading. Petrographic and sedimentary features include ooids and convoluted or overturned beds attributed to mass sediment movement down the palaeoslope (Tucker 1986).

Boundary relations with overlying and underlying non-glacial units

Contact with underlying units

The contact underlying the glaciogenic interval of the KPF is complex and does not represent a single timeline, as it is located above both an older and younger unconformity. The older unconformity is preserved in hanging wall sections and separates the KP2 Member from a beveled contact with either the Virgin Spring limestone or the underlying KP1 Member. The younger unconformity occurs in footwall sections and variably separates the KP4 Member from a beveled contact with either of the two underlying formations of the Pahrump Group (Beck Springs Dolomite or Crystal Springs Fm.) or the granitic basement. This younger unconformity developed due to erosion from uplift of footwall blocks, which removed the older unconformity as well as variable intervals of the Pahrump Group, down to the underlying basement.

In hanging wall sections where the contact between the non-glacial units of the eastern-KPF and the underlying Beck Spring Dolomite is preserved, it has been described as conformable, interfingering or unconformable (Christie-Blick & Levy 1989) and shows no evidence of erosional truncation, although Kenny & Knauth (2001) describe karstification of the upper Beck Spring Dolomite in some localities. In the Alexander Hills and Saratoga Hills, the KP1 Member is described as transitional with the top of the Beck Spring Dolomite over 10 m (Wright *et al.* 1992). This relationship can be seen in the Alexander Hills (35°46′2″N, 116°7′10″W, #1 in Fig. 40.1) and in the southern Black Mountains (35°54′45″N, 116°38′50″W, #23 in Fig. 40.1) where there is a sharp contact between the Beck Spring Dolomite and the KP1 Member sandstone, followed by interbedding between centimetre-scale dolomite and sandstone beds over the next several metres.

Contact with the overlying Noonday Dolomite

The contact between the eastern-KPF and the overlying Noonday Dolomite is contentious and has been reported as regionally unconformable (Noble 1934; Wright *et al.* 1978), locally unconformable (Christie-Blick & Levy 1989) and locally conformable (Miller 1987). An unconformable relationship has been suggested because the Noonday Dolomite seems to cap successively older, seemingly tilted, strata (Cloud *et al.* 1974; Wright *et al.* 1976) between the Alexander Hills and the southern Nopah Range, ultimately straddling the contact between the Crystal Spring Fm. and the basement at the War Eagle Mine. Alternatively, Prave (1999) suggested the Gunsight Member infills erosional topography and is conformable with the overlying Noonday Dolomite.

Field studies by the authors (see also Mrofka 2010) provide evidence for uninterrupted deposition beginning at the base of the KP2 Member and continuing through the Noonday Dolomite, demonstrated by the following four sedimentary relationships. First, KP4 Member sedimentary breccias in the Alexander Hills are interbedded with the basal Noonday Dolomite (35°45′56″N, 116°6′55″W). Second, in footwall sections the contact between the Noonday Dolomite and underlying strata is commonly interrupted by a 1–10 m layer of Gunsight Member diamictite; a similar diamictite interval appears conformable with the underlying KP4 Member in hanging wall sections. Third, in the southern Valjean Hills (35°39′40″N, 116°7′22″W, #17 in Fig. 40.1) and in the Ibex Hills (DeYoung pers. comm.), Noonday Dolomite clasts are included in diamictite of the KP4 member or are in diamictite interbedded with KP4 Member sedimentary breccia. Alternatively, Corsetti & Kaufman (2005) interpreted this Ibex Hills interbedded diamictite to post-date KPF deposition. Fourth, the base of the Noonday Dolomite commonly contains clasts from the Beck Spring Dolomite and Crystal Spring Fm. (i.e. 35°45′46″N, 116°6′50″W). This relationship is consistently observed when the Noonday Dolomite overlies the KP4 Member. Furthermore, the Beck Spring Dolomite or Crystal Spring Fm. has not been found in direct contact with the Noonday Dolomite. This likely indicates that during incipient Noonday Dolomite deposition, loose clasts from the surface of an unlithified KP4 Member were reworked along with carbonate material from the flanks of Noonday Dolomite mounds. Alternatively, the Pahrump Group may have been exposed during Noonday Dolomite deposition, serving as a source of clasts in the basal Noonday Dolomite, and contacts between the two are simply not exposed.

Chemostratigraphy

The most prominent carbonate units within the KPF succession are the Virgin Spring limestone and the KP3 Member oncolitic dolostone bed in the northern facies, the Silurian Hills limestone in the southern facies and the Sourdough Limestone in the western-KPF (Fig. 40.1). Statistics for published isotopic data for prominent carbonate units within and bounding the KPF are listed in Table 40.1 (Tucker 1983, 1986; Bergfeld *et al.* 1996; Kennedy *et al.* 2001*a*; Corsetti & Kaufman 2003). Eastern-KPF carbonates have relatively enriched $\delta^{13}C$ and depleted $\delta^{18}O$ values, and data from published stratigraphic profiles (Tucker

Table 40.1. *Range of C- and O-isotopic values for carbonate associated with the KPF*

Unit	Delta	Min.	Max.	Average	Median	SD
Beck Spring	$\delta^{13}C_{carb}$	−4.4	5.8	2.7	3.0	1.8
Dolomite	$\delta^{18}O$	−18.0	1.3	−6.0	−5.5	3.8
$n = 259$	$\delta^{13}C_{org}$ ($n = 45$)	−25.9	0.7	−18.4	−18.6	4.3
KPF Oncolite	$\delta^{13}C_{carb}$	−4.0	1.1	−1.6	−2.0	1.5
Marker Bed	$\delta^{18}O$	−11.2	−2.1	−6.1	−5.8	2.7
$n = 13$	$\delta^{13}C_{org}$					
Virgin Spring	$\delta^{13}C_{carb}$	1.0	2.4	2.4	2.1	1.3
Limestone	$\delta^{18}O$	−16.2	−12.5	−15.4	−15.6	1.0
$n = 11$	$\delta^{13}C_{org}$					
Sourdough	$\delta^{13}C_{carb}$	−7	3.9	−0.2	−0.8	2.7
Limestone	$\delta^{18}O$	−16.9	−8.3	−13.3	−13.6	2.1
$n = 45$	$\delta^{13}C_{org}$ ($n = 9$)	−15.0	−4.4	−7.9	−6.7	3.7
Noonday	$\delta^{13}C_{carb}$	−4.2	−0.9	−2.8	−2.7	1.1
Dolomite	$\delta^{18}O$	−11.3	−4.0	−6.9	−6.5	3.1
$n = 22$	$\delta^{13}C_{org}$ ($n = 9$)	−25.6	−17.6	−21.3	−21.3	2.5

Data from Tucker (1983, 1986); Bergfeld *et al.* (1996); Kennedy *et al.* (2001*a*) and Corsetti & Kaufman (2003).

1986; Prave 1999; Corsetti & Kaufman 2003) for $\delta^{13}C$ and $\delta^{18}O$ identify no clear stratigraphic trends within the KPF succession.

On the other hand, distinctive isotopic values and spatial continuity of the Beck Spring Dolomite and the Noonday Dolomite bracket the KPF and provide a clear stratigraphic and geochemical framework for the KPF. The Beck Spring Dolomite shows a several per mille enrichment in $\delta^{13}C$ above the base of the Formation (Corsetti & Kaufman 2003) and has enriched $\delta^{13}C$ and $\delta^{18}O$ values overall (Table 40.1). Noonday Dolomite $\delta^{13}C$ and $\delta^{18}O$ values for the overlying Noonday Dolomite show a moderate positive co-variation ($r^2 = 0.3$) and Kennedy *et al.* (1998, 2001*a*) pointed out the similarity between the negative-to-positive $\delta^{13}C$ trend in the base of the Noonday Dolomite and similar trends in other late Cryogenian cap carbonates. Hurtgen *et al.* (2004) published $^{34}S_{sulphate}$ values for the Beck Spring Dolomite and the Noonday Dolomite in the range 11.0–27.4‰ and 15–35‰, respectively, and suggested the values were evidence of ocean sulphate concentrations at 10% of modern values during the mid-Proterozoic with a transition to higher values in the late Proterozoic, possibly due to glaciation.

Other characteristics

Corsetti *et al.* (2003) documented complex microfossils preserved in chert and carbonate from the oncolitic dolostone bed within the KP3 Member, similar to microfossils identified in chert nodules from the Beck Spring Dolomite (Pierce & Cloud 1979; Horodyski & Knauth 1994). Microfossil evidence was used to support the existence of active shallow-water microbial biota during a Cryogenian glaciation, in which biological activity was thought to have been non-existent (Hoffman *et al.* 1998).

Palaeolatitude and palaeogeography

There is no published palaeolatitude data for the KPF itself and palaeomagnetism test holes in the KP3 Member in the Alexander Hills yielded data that showed later remagnetization (Wright 2002, pers. comm.). Evans (2000, p. 365, fig. 3) estimated a *c.* 9° palaeolatitude for the KPF at 723 ± 3 Ma based on correlation with other Neoproterozoic strata along the North American Cordillera and proposed a nearly equivalent line of latitude with the Toby Fm. (Christie & Fahrig 1983; Heaman *et al.* 1992). However, given Cryogenian Period glacial episodes occur between *c.* 750–634 Ma (Condon *et al.* 2005; Kendall *et al.* 2006) and the lack of geochronological constraints on KPF deposition, the 9° palaeolatitude is highly equivocal.

Geochronological constraints

The KPF is poorly constrained by a date of 1.08 Ga from diabase within the middle member of the Crystal Spring Fm. (Heaman & Grotzinger 1992), 500–1000 m below the base of the KPF, and the Precambrian–Cambrian Boundary in the lower member of the Wood Canyon Fm. (Corsetti & Hagadorn 2000), 2000 m above the base of the Noonday Dolomite (Fig. 40.1). Deposition of broadly similar (but not necessarily correlative) coarse-grained strata in Idaho is bounded by a lower limit of 717 ± 4 Ma and 701 ± 4 Ma (Fanning & Link 2004, 2008; U–Pb SHRIMP on a volcanic clast in diamictite) and upper limit of 685 ± 7 Ma (Lund *et al.* 2003, U–Pb SHRIMP) and 667 ± 5 Ma (Fanning & Link 2004; U–Pb SHRIMP based on tuff above overlying carbonate).

Discussion

Tectonic and glacial deposits of the eastern-KPF are associated with the underlying Beck Spring Dolomite and overlying Noonday Dolomite carbonate platforms, overlie a regional unconformity and record an abrupt change to siliciclastic sedimentation resulting from tectonic uplift. The wedge-shaped packaging of the KPF strata next to tilted and erosionally truncated segments of the underlying Pahrump Group and basement is consistent with successions that accumulate during rotation of hanging wall and footwall sections in extensional systems (Jackson & White 1988; Faerseth *et al.* 1990, p. 1291, fig. 7; Jackson *et al.* 2005). Coarse-grained facies, initiated with deposition of the KP2 Member, are primarily the product of local tectonic activity as indicated by (i) syndepositional normal faults and erosional bevelling of footwall blocks, (ii) a systematic and consistent pattern of coarsening upwards from sand and angular cobble debrites to sedimentary breccia and kilometre-scale olistoliths, (iii) a transition from marine debris-flow facies to terrestrial fanglomerates and (iv) a systematic pattern of unroofing of the underlying Pahrump group as seen in the sequence of dominant clasts. A coarsening-upwards trend beginning in the upper KP3 Member and the transition to terrestrial fanglomerates in the KP4 Member, especially near basin margins, indicate shallowing as deposition outpaces subsidence and creation of accommodation space. The occurrence of striated clasts in the KP2 and KP3 members indicates a glaciogenic influence that is sporadic and limited to specific stratigraphic intervals.

The KP1 Member parallel-laminated sandstone was interpreted by Tucker (1986) as having been deposited on a shelf by storm currents and the overlying laminated Virgin Spring limestone representing a relatively deeper water carbonate environment with periodic input of sand and ooids by storms. The unconformity that truncates the Virgin Spring limestone might be a result of sea-level fall from glaciation or tectonic uplift. Erosional truncation in hanging wall sections indicates that while clasts from the underlying Pahrump Group in the KP2 Member provide a clear signal for initiation of tectonism, initial exposure and erosion across the region may have been the result of ice growth and sea-level change prior to local tectonism, as indicated by the presence of striated clasts.

The KP2 Member was likely deposited in a glaciomarine setting and underwent downslope reworking (Boulton & Deynoux 1981) on the same broad shallow shelf on which the KP1 Member and Virgin Spring limestone were deposited. There is no evidence of the clinoform geometry or rapid lateral facies changes expected with ice-proximal debris aprons and no evidence of laminations within the diamictite facies hosting outsized clasts expected from rainout of ice-rafted debris. The KP3 Member records the greatest lateral thickness changes of all the KPF members and represents the most active phase of tectonism in the KPF, perhaps equivalent to a rift climax (Prosser 1993). Diamictite intervals within the KP3 Member with striated clasts are interbedded with coarse-grained deposits interpreted to be a result of gravity-driven debris flows of glaciogenic debris down a rapidly tectonically steepening margin. The KP4 Member is dominated by commonly monomictic channelized sedimentary breccia and likely represents terrestrial fanglomerate (Hewett 1956). Lateral inter-fingering relations evident in the Kingston Range between fanglomerate facies and turbiditic sandstone suggest the KP4 Member is a terrestrial equivalent of the more distal, marine KP3 Member, indicating fan-building progressed sub-aqueously and mixed with finer-grained distal density deposits.

The Gunsight Member records a final pulse of glaciation and subsequent deglacial flooding of KP4 Member terrestrial deposits. The abrupt and conformable transition to the overlying, regionally continuous, platformal Noonday Dolomite, as well as the thickness of the dolomite's microbial mounds (>200 m) suggest flooding was a result of deglacial sea-level rise, and that continued transgression and cessation of tectonism completely cut off any source of siliciclastic sediments.

Association with Neoproterozoic glaciation

The only direct evidence for glaciation in the KPF is striated clast-bearing diamictite (Hazzard 1939; Miller 1985) found throughout the KP2 Member, interbedded in the lower half of the KP3 Member and commonly comprising the Gunsight Member. Striated clasts are polished, comprised of siltstone, chert and quartzite, and rarely faceted. There is no systematic relationship between striated clast-bearing diamictite and bounding units; in the KP2 Member diamictite is overlain sharply by sandstone of the basal KP3 Member, in the KP3 Member diamictite is interbedded with sandstone and sedimentary breccia and in the Gunsight Member it sharply overlies sedimentary breccia. Indirect evidence for a glacial influence (Crowell 1999) in the KPF was documented by Miller (1985) in both the western and eastern-KPF and includes evidence for rapid deposition, presence of diamictite and rapid lateral changes in facies and thickness.

Sediments with striated clasts are often attributed to ice-rafted debris in glaciomarine settings (Crowell 1999). At Sperry Wash (35°42′13″N, 116°14′34″W, #18 in Fig. 40.1) outsized clasts within turbidite facies (Troxel 1982*b*) of the KP3 Member have been interpreted as dropstones (Abolins *et al.* 2000; Corsetti & Kaufman 2003) or as lone clasts rolling down tectonically produced slopes (Troxel 1982*b*). Several clasts appear to deform underlying sediments and at least one pierces underlying sediments and may have splash-marks (Corsetti pers. comm. 2008). However, outsized clasts at Sperry Wash are grouped along common bedding planes and laterally associated with diamictites and normally graded conglomerate beds interpreted to be debris flows (Troxel 1982*b*). In other sections, similar outsized clast-bearing facies are interbedded with conglomerate and host megaclasts (tens of metres scale) and kilometre-scale olistoliths. The association with tectonically emplaced olistoliths, the bedding plane parallel orientation of many clasts and close association of outsize clasts to debrites beds with lonestones, suggests outsized clasts may alternatively represent the distal edges of debris flows or loose clasts that tumbled down clast-laden slopes (Postma *et al.* 1988).

The KP3 Member at Sperry Wash contains up to 45% Fe by weight (Abolins *et al.* 2000) and due to association between Fe-rich sediments and Neoproterozoic glacial intervals (Young 1976), has been interpreted to represent evidence for glaciation (Stewart 1972; Abolins *et al.* 2000; Awramik *et al.* 2000). However, there is no direct evidence for an oceanographic origin for the Fe. Alternatively, the Fe might be associated with nearby Tertiary-aged volcanic intrusions.

Neoproterozoic glacial sediments are commonly intimately associated with overlying carbonate facies (Hoffman *et al.* 1998). These cap carbonates typically overlie an older and younger glacial interval in many sections and host a variety of distinctive sedimentary and geochemical features (Kennedy *et al.* 1998; Hoffman *et al.* 2002). The Sourdough Limestone Member in the western-KPF is characterized by graphite-rich parallel laminations and depleted $\delta^{13}C$ values (Table 40.1), characteristics shared among older Cryogenian cap carbonates (Kennedy *et al.* 1998), and has been interpreted to represent an older cap carbonate in the western-KPF (Prave 1999). In the eastern-KPF, the Virgin Spring and Silurian Hills limestone units are also characterized by graphite-rich parallel laminations but have enriched $\delta^{13}C$ values (Table 40.1). The Noonday Dolomite, interpreted to represent a younger cap carbonate (Prave 1999), overlies the KPF and shares a number of characteristics with other younger cap carbonates, including its cream colour, tubestones, abundant marine cements and depleted $\delta^{13}C$ values (Kennedy *et al.* 1998; Nogueira *et al*. 2003).

Carbonate intervals in both eastern and western KPF intervals are associated with coarse-grained facies but litho-stratigraphic correlation is complicated by dissimilar bounding lithofacies. Deposition and a sporadic glacial influence are continuous from the KP2 Member through the Noonday Dolomite, so the interval does not conform to a glacial–cap carbonate–interglacial–glacial–cap carbonate cycle typical of other Neoproterozoic successions. Although associated with coarse-grained facies, the palaeoclimatic significance of the carbonate intervals in the eastern KPF is unclear.

Conclusion

The Kingston Peak Fm. in the Death Valley region is one of the few areas in the southern Cordillera where the association between extension and resulting Neoproterozoic sedimentation is clear (Burchfiel *et al.* 1992). This allows three competing hypotheses for the origin of Neoproterozoic glacial deposits to be tested: (1) glacial sediments record a globally synchronous climate event (Snowball Earth); (2) glacial sediments record regional glaciation attributed to tectonism and terminated with the cessation of extension (i.e. zipper-rift model of Eyles & Januszczak (2004)); and (3) glacial sediments comprise an incomplete record of either regional glaciation or a long-term (50–100 Ma) Cryogenian glacial era (Allen & Etienne 2008) with sedimentary evidence of glaciation only preserved during periods of tectonism and generation of accommodation space. In hypothesis two and three, the preservation of glaciogenic sediments is linked with regional tectonism and therefore results in a diachronous record of glaciation.

Each of the three hypotheses results in specific predictions for the sedimentary record. In the first case, if the transgressive deposits of the Noonday Dolomite are related to global deglaciation and not cessation of extension, syn-depositional faulting should continue through the Noonday Dolomite. This has not been observed. In the second case, carbonate deposition is related to transgression during thermal subsidence when tectonism ends; rising sea level confines glacial evidence up-dip or may be entirely lacking because of slowdown in adiabatic cooling provided by uplift. In the last case, extension and uplift provide accommodation space in shallow marine to terrestrial environments that rapidly preserve glacial sediments and provide a record of glaciation and climate change whose continuity and completeness is controlled by local tectonism.

The intimate association between localized tectonically created uplift, accommodation space, and conglomeratic facies bring into question the suggestion that KPF strata record a regional component of synchronous glacial sedimentation associated with global Neoproterozoic ice ages (Prave 1999). The complete lack of geochronological data makes any global inference problematic. Evidence in the Kingston Peak Fm. provides more support for hypotheses two and three and consequently a strong argument for diachronous glacial deposition and cap carbonate deposition. These data support the argument that the Kingston Peak Fm., along with an increasing number of other Neoproterozoic deposits worldwide (Allen & Etienne 2008), record part of a continual and diachronous climate record (Mrofka 2010) spanning the Cryogenian Period.

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