NEOPROTEROZOIC CARBONATE SUCCESSIONS, DEATH VALLEY, CALIFORNIA: COMPARISON AND CONTRAST WITH PHANEROZOIC EXAMPLES

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INTRODUCTION

The study of Phanerozoic carbonate platforms has had a long, successful scientific history producing a wealth of information regarding carbonate genesis and implications for unraveling paleoclimatic and paleo-oceanographic conditions, eustatic variations, and basin evolution (*e.g.*, Heckel, 1974; Ginsburg and Klein, 1975; Wilson, 1975; Hardie, 1977; Goldhammer and others 1987; Read, 1985; Tucker and Wright, 1990). Over the past decade or so, several workers have had similar success in documenting and understanding the genesis of Precambrian carbonate rocks (e.g., Bertrand-Sarfarti and Moussine-Pouchkine, 1983; Beukes, 1987; Derry and others, 1989; Eriksson, 1977; Grotzinger, 1986a,b, 1989; Hoffman, 1975; Kaufman and Knoll, 1995; Knoll and Swett, 1990; Tucker, 1983; Zempolich and others, 1988). In fact, it is a consequence of studies on Precambrian carbonates that we in the geoscience community are presently in the privileged position of witnessing firsthand the exciting insights being obtained to help resolve problems as fundamental as the evolution and emergence of early life to secular variations in atmospheric and oceanic composition of the earth system (*e.g.*, Grotzinger, 1994; Knoll, 1991; Knoll and Walter, 1992).

The foundation for such studies rests on detailed field observations, facies descriptions, and their proper interpretation. Thus, the theme of this field trip is to introduce you to the facies character and architecture of two wonderfully exposed Proterozoic carbonate platforms in the Death Valley region, the Mesoproterozoic middle member Crystal Spring Formation and the Neoproterozoic Beck Spring Dolomite. These rocks display many of the depositional components recognized from their Phanerozoic counterparts such as meters-scaled peritidal shoaling cycles, pendant and isopachous cements, oolitic shoals, foreslope rhythmites and breccias, and stromatolitic buildups (analogous to their biomineralized Phanerozoic relatives, reefs). In addition, my preliminary results regarding the geodynamic setting of these two units indicate dissimilar tectonostratigraphic settings: the middle Crystal Spring platform displays uniform thickness and facies character throughout the study area and apparently met its demise due to a relative drop in sea level (as implied by karst development in its uppermost part), whereas the Beck Spring platform displays considerable lateral change in stratal character and appears to have been gradually drowned beneath an encroaching blanket of deepwater, fine grained siliciclastics. Note that I present this trip to you more in the form of a progress report rather than a finely honed finished product. My work on these rocks is ongoing and I welcome the opportunity for insights and discussions.

GEOLOGIC SETTING

The Proterozoic through Lower Cambrian rocks of the Death Valley region have been generally viewed within the framework of a tripartite subdivision consisting of: (1) a 1.7 to 1.4 Ga basement complex of mostly quartzofeldspathic gneiss and metasedimentary units (Wasserburg and others, 1959; Silver and others, 1961; Labotka and Albee, 1977; Dewitt and others, 1984); (2) a nonconformably overlying sedimentary succession, the Pahrump Group (defined by Hewitt, 1956), composed of mixed siliciclastic and carbonate rocks locally containing basic sills and flows; and (3) a younger Proterozoic through Lower Cambrian succession of sedimentary strata (Figs. 1 and 2). At present, the exact nature of the tectonostratigraphic evolution of this part of the Laurentian craton as recorded by the Pahrump and younger Proterozoic rocks remains conjectural and the subject of ongoing investigation. What is generally accepted, though, is that most of these rocks predate the inception of the Cordilleran passive margin as marked by the onset of thermo-mechanicalsubsidence around 0.55 to 0.59 Ga (Stewart, 1972; Armin and Mayer, 1983; Bond and others, 1985; Levy and Christie-Blick, 1991).

With regard to the Pahrump Group, previous workers inferred an overall extensional tectonic setting and suggested that its depositional culmination was within a rather narrow, deep basin oriented at a high angle to the craton margin (the Amargosa aulacogen of Wright and others, 1976). That interpretation was largely dependent upon two assumptions: (1) the Pahrump succession was essentially conformable; and (2) the present geographic distribution of range blocks more-or-less reflects original paleogeographic relationships

in Patrick L. Abbott and John D. Cooper., eds., 1996,
Field Conference Guide 1996. Pacific Section A.A.P.G, GB 73,
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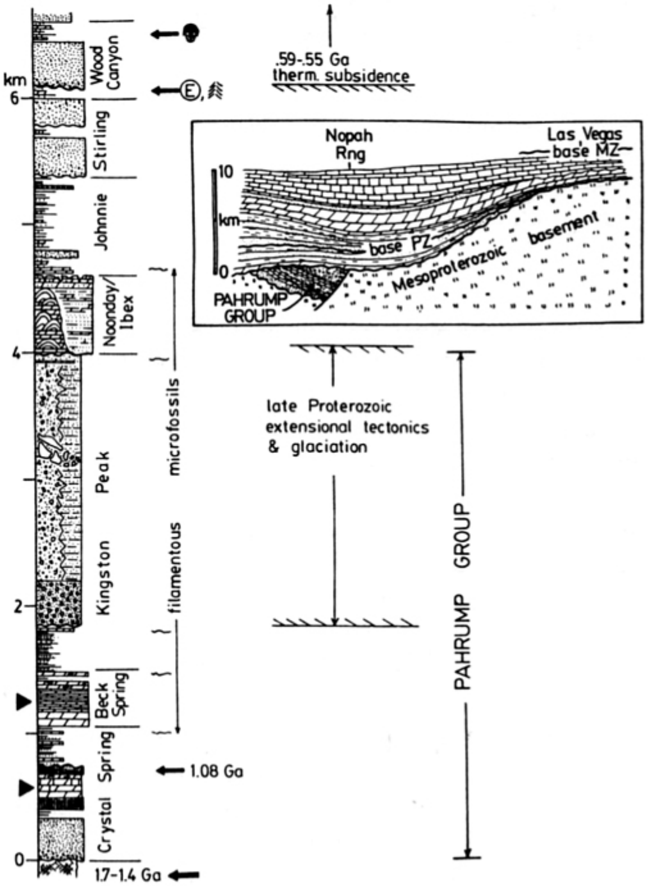


Figure 1. Generalized stratigraphic column for the Pahrump Group (Crystal Spring, Beck Spring and Kingston Peak Formations) and younger Proterozoic rocks in the Death Valley region. Bold arrows to right of column show locations of absolute age determinations (basement ages and U-Pb age from Heaman and Grotzinger, 1992, for diabase sills in the Crystal Spring Fm) and base Cambrian biostratigraphic intervals (E-Ediacaran and Paleozoic-like traces in lower Wood Canyon Fm and first trilobites in upper Wood Canyon Fm; Horodyski, 1991; Diehl, 1976). Also shown are the locations from which filamentous microfossils have been reported (*e.g.*, Horodyski and Knauth, 1994; Pierce and Cloud, 1979). The units of interest for this trip, the middle Crystal Spring and Beck Spring rocks, are identified by the solid triangles to the left of column. The west to east stratigraphic cross-section depicted in the inset shows diagrammatically the position of the Pahrump Group unconformably beneath the cratonward-tapering wedge of the Cordilleran miogeoclinal units (PZ-Paleozoic; MZ-Mesozoic; see Fig. 2 for location of Nopah Range).

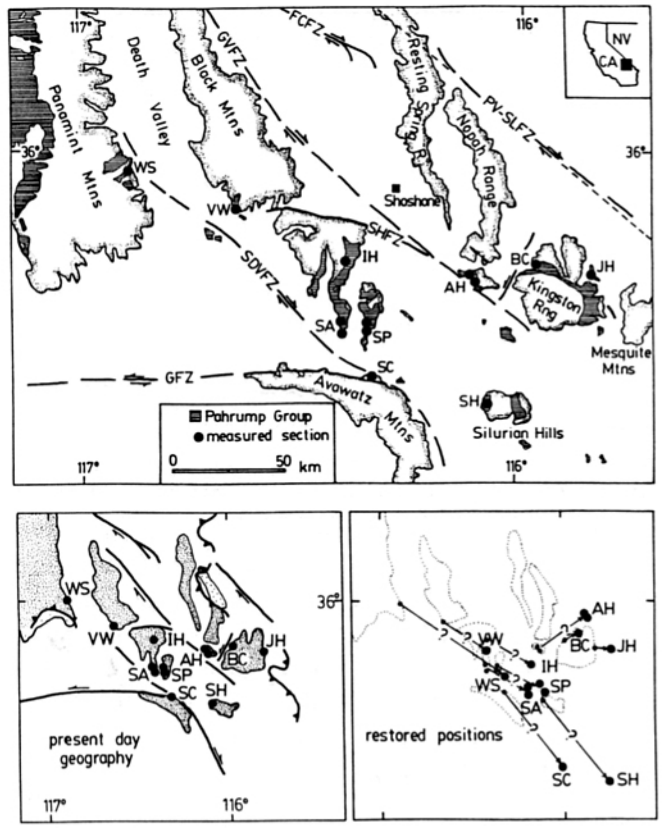


Figure 2. Upper map shows Pahrump Group outcrops and major strike-slip fault zones in the southern Death Valley area: FCFZ-Furnace Creek fault zone; GFZ-Garlock fault zone; GVFZ-Grandview fault zone; PVSLFZ-Pahrump Valley/State Line fault zone; SDVFZ-southern Death Valley fault zone; SHFZ-Sheephead fault zone. Solid circles indicate locations of measured sections: AH-Alexander Hills (two sections); BC-Beck Canyon; IH-Ibex Hills; JH-Jupiter Hill; SA-Saratoga Hills (two sections); SC-Sheep Creek; SH-Silurian Hills; SP-Saddle Peak Hills (two sections); VW-Virgin Spring Wash; WS-Warm Springs Canyon. Lower left map shows the Wheeler Pass thrust plate (heavier stippling) of Wernicke and others (1988); faults shown are the major strike-slip fault zones and trace of the Wheeler Pass (and equivalent) thrust fault. Lower right map shows best-estimate palinspastic reconstruction accounting for Mesozoic and Cenozoic tectonic disruptions.

between sections. Recent reinvestigation of the Pahrump rocks principally by myself (*e.g.*, Prave, 1994, and unpub. data; Mbuyi and Prave, 1993) has shown that the first assumption is incorrect; several major unconformities, and other numerous hiatal surfaces, cut through the Pahrump Group. Additionally, the two main post-Pahrump deformational episodes that tectonically dismembered the southwestern Great Basin, the dauntingly complicated Neogene extension superimposed on Mesozoic contractile deformation, are now known to be noncoaxial and of greatly dissimilar magnitude. Consequently, they must be accounted for and palinspastically compensated (*e.g.*, Stewart, 1983; Prave and Wright, 1986; Levy and Christie-Blick, 1989; Snow and Prave, 1994; Topping, 1993). The most widely cited (and debated) palinspastic reconstruction for the Death Valley region is that championed by Wernicke and colleagues (Wernicke and others, 1988; Snow and Wernicke, 1989) who match offset contractile structures to construct a Mesozoic template for the southwestern Great Basin. In general, this model indicates that about 250% extension along northwest-directed vector paths stretched the lithosphere in the region between Las Vegas and the Sierra Nevada. Even though most workers concur that the Death Valley region has undergone severe extensional telescoping, the magnitude and style of extension proposed by Wernicke and colleagues remain a topic of lively debate. Nonetheless, this model does provide the basis for sedimentologically and stratigraphically assessing the resulting reconstructed paleogeographies.

In the southern Death Valley region, palinspastic reconstruction of range blocks (including those we will visit during this field trip, see Fig. 2) must account for several additional complications related to: (1) southwest-directed tectonic translation on high-angle faults along the northwestern flank of the Kingston Range (Topping, 1993; unpublished mapping by Troxel, McMackin and Wright); and (2) the lack of constraints for the amount of translation along the southern extension of the Death Valley fault zone. I have used the published reconstructions (*e.g.*, Wernicke and others, 1988; Topping, 1993) coupled with unpublished data (pers. comm., 1996, Wright, Troxel, McMackin, Wernicke, Snow, and Cooper) to construct a tentative best-estimate approximation of a Neoproterozoic palinspastic reconstruction for the range blocks within the southern Death Valley region (bottom-right inset on Fig. 2). Although I am certain that the reconstruction shown on Figure 2 will be modified as more data are assimilated, it nonetheless represents a more accurate base map from which to assess Neoproterozoic paleogeography and basinal dynamics than that of the present range distributions (note that Fig. 2 is used as the basis for the stratigraphic cross-sections shown for the middle Crystal Spring and Beck Spring carbonate platforms in this paper).

The Proterozoic Pahrump Group

The Pahrump Group is a mostly sedimentary succession which, in its most complete development, varies between 3 to 5 km thick. Three formations comprise this Group, in ascending order, the Crystal Spring Formation, Beck Spring Dolomite, and Kingston Peak Formation (Fig. 1). The basal Crystal Spring strata consist of a several hundred meters-thick package of arkosic to quartzitic sandstone, conglomerate and mudstone that rests nonconformably on gneissic and crystalline basement rocks. These strata record deposition in braided fluvial and associated systems (Roberts, 1974, 1976) arrayed around and draining off block-faulted uplands in the vicinity of the Nopah-Resting Spring Ranges and possibly in the central Panamint Mountains (the Nopah Upland and World Beater Islands of, respectively, Wright and Troxel, 1966, and Labotka and Albee, 1977).

The coarse siliciclastic strata of the lower Crystal Spring are gradationally overlain by finer sandstones and mudstones which pass upward into the carbonate rocks of the middle Crystal Spring Formation. It is this carbonate unit which will be the focus of Stop 2 in the Alexander Hills during Day 1 and Stop 1 in the Saratoga Hills during Day 2 of the field trip (Fig. 3). The middle Crystal Spring carbonate platform is between 100 and 200 m thick and consists of a lower unit of cyclically arranged peritidal shoaling cycles (ribbon rock to microbial laminites) and an upper stromatolitic biostrome with interbedded intraclastic grainstone and oolitic beds. In many places, the uppermost part of this platform displays evidence of karst (clastic infilled grikes, karstic breccias, pendant cements and geopetal fabrics in sheet cracks, *etc.*). Note that it is within the lower and middle Crystal Spring Formation that the ~1.08 Ga (Heaman and Grotzinger, 1992) diabasic sills and dikes intrude. The once economically-mined calcsilicate ('talc') ore bodies (such as those we will see in the abandoned workings of the Western Talc Mine in the Alexander Hills during Stop 3 of Day 1) are a result of the contact metamorphism between these igneous intrusions and the middle Crystal Spring carbonate rocks (Wright, 1968).

Overlying the middle Crystal Spring strata is a 50 to 500 m-thick mixed siliciclastic-carbonate assemblage of nearshore marine, peritidal, and distal fluvial sandstones, mudstones, and microbial laminated dolostones (Mbuyi and Prave, 1992, 1993; Maud, 1979) which comprise the rocks of the upper Crystal Spring Formation (we will see these strata at Stop 2 Day 1 and walk across them in the Saratoga Hills during Day 2). Until recently, these upper Crystal Spring units were assumed to rest conformably on the middle Crystal Spring carbonate rocks. However, detailed facies analyses and mapping by Mbuyi and Prave (1992, 1993) and Prave (1994; unpub. data) have revealed the presence of several hiatal surfaces within the upper Crystal Spring strata. Although the temporal magnitudes of these hiatuses are not known, the singlemost critical observation is that the base of the upper member Crystal Spring Formation defines a regional angular unconformity which cuts across the underlying hornfelsic and diabasic rocks of the middle Crystal Spring Formation. This indicates that the upper Crystal Spring and overlying rocks are considerably younger than the 1.08 Ga diabase intrusions. It is interesting that, even though these unconformities went unrecognized, facies changes from finer siliciclastics and carbonates in northern localities to mostly coarser siliciclastics in the Silurian Hills led Wright and others (1976) to postulate the onset of tectonism during upper member Crystal Spring time in the form of an uplifting southern provenance they termed the Mojave Upland. More on this during the fieldtrip.

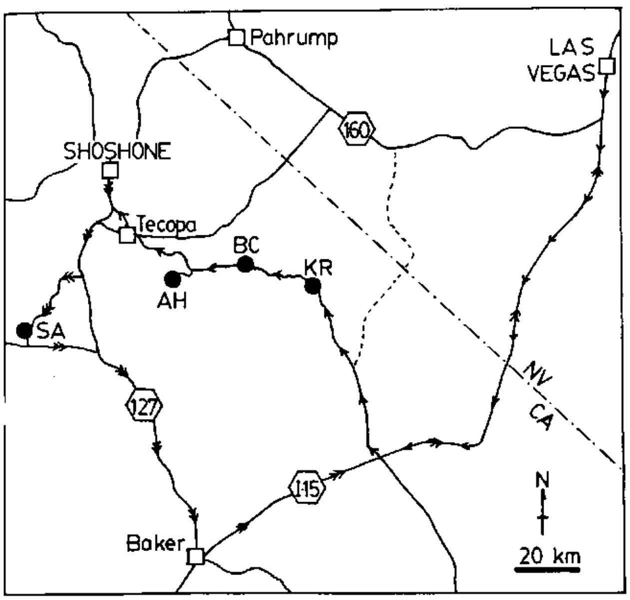


Figure 3. Location map of field trip area showing daily route coverage and field trip stops: KR-eastern Kingston Range (Stop1 Day1); BC-western mouth of Beck Canyon (Stop 2 Day 1); AH-Western Talc Mine Alexander Hills (Stop 3 Day 1); SA-southern end of Saratoga Hills (Stop 1 Day 2).

The second major carbonate package in the Pahrump Group is the 200 to 500 m-thick Beck Spring Dolomite. This unit is the focus of Stop 1 Day 1 in Beck Canyon and most of Stop 1 Day 2 in the Saratoga Hills (Fig. 3). The Beck Spring Dolomite records an overall shoaling succession from slope rhythmites and breccias to shallow-water oolitic shoals, intraclastic grainstones, and stromatolitic bioherms/stromes (Gutstadt, 1968; Marian, 1979; Marian and Osborne, 1992; Shafer, 1983; Prave, unpub. data). In an apparently transitional contact, the Beck Spring carbonates gradationally pass upward into laminated and graded mudstones and fine sandstones of the basal Kingston Peak Formation. This transition reflects the gradual drowning and collapse of the Beck Spring platform and its blanketing by the influx of basal Kingston Peak siliciclastics.

Regardless of the exact geodynamic context within which the Crystal Spring and Beck Spring rocks were deposited (again, more on this and my ongoing research program focussing on reevaluating the tectonostratigraphic evolution of the Pahrump Group and its geodynamical basinal context during the field trip), the abrupt influx of coarse sediment gravity flow deposits and olistoliths in the middle and upper Kingston Peak Formation signal the onset of active tectonism. The base middle member Kingston Peak Formation is a major unconformity surface and the rocks above that surface contain pebble to house-size clasts cannibalized from the underlying Pahrump units and basement rocks. It is within these strata that lonestones, dropstones, and striated and faceted pebbles are found and have been used as evidence for a glacigenic influence on Kingston Peak sedimentation (Hazzard, 1939; Troxel, 1966; Miller, 1985; Miller and others, 1988). An absolute age for the Kingston Peak glaciation has yet to be established but, as inferred by Miller (1985, 1987), a 600-750 Ma age can be assumed based on correlation to other such strata elsewhere (I am currently processing ash-like beds sampled from the upper Kingston Peak and have sampled the overlying Noonday Dolomite for C-isotope analyses and should hopefully be able to determine if these rocks are of Sturtian or Varanger age). The Pahrump basin is effectively sealed by the unconformably overlying Noonday Dolomite platform carbonate or its basinal equivalent, the Ibex Formation. Thus, although age constraints are loose, the Pahrump Group spans between 300 Ma to potentially 800 Ma of geological time!

MIDDLE MEMBER CRYSTAL SPRING CARBONATE PLATFORM

The middle Crystal Spring carbonate platform can be grossly viewed as consisting of a facies couplet (Wright, 1968; Roberts, 1982; Prave, unpub. data): a lower unit of commonly cherty dolostone and an upper stromatolitic limestone-dolostone unit. Combined, these two lithofacies comprise a northward-thickening carbonate platform, from about 100 m in the Saratoga Hills to 200 m in the Alexander Hills (Figs. 2 and 4).

Everywhere in the Death Valley region, the depositional base of the middle member Crystal Spring Formation is obscured by the emplacement of diabasic sills; intrusive emplacement of these bodies must have been controlled by the proper combination of lithologic contrast (underlying mudstones of the lower Crystal Spring Formation versus the overlying middle member carbonate unit) and overburden pressures characterizing this stratigraphic horizon. Although the diabase is known to be slightly discordant to bedding, regional facies relationships coupled with detailed mapping suggest that not much section is 'lost' due to the intrusions (Wright, 1968; Prave, unpub. data). Thus, it appears that the transition from tidal flat and shallow-marine siliciclastics in the upper part of the lower member Crystal Spring to the carbonate rocks of the lower part of the middle Crystal Spring carbonate unit is gradational.

Everywhere above the highly altered calcsilicate rock ('talc') in contact with the diabase, the first carbonate beds of the middle member Crystal Spring Formation consist of highly silicified and cherty dolostone which pass upsection into non-cherty dolostone and limestone. The degree of silicification increases with proximity to

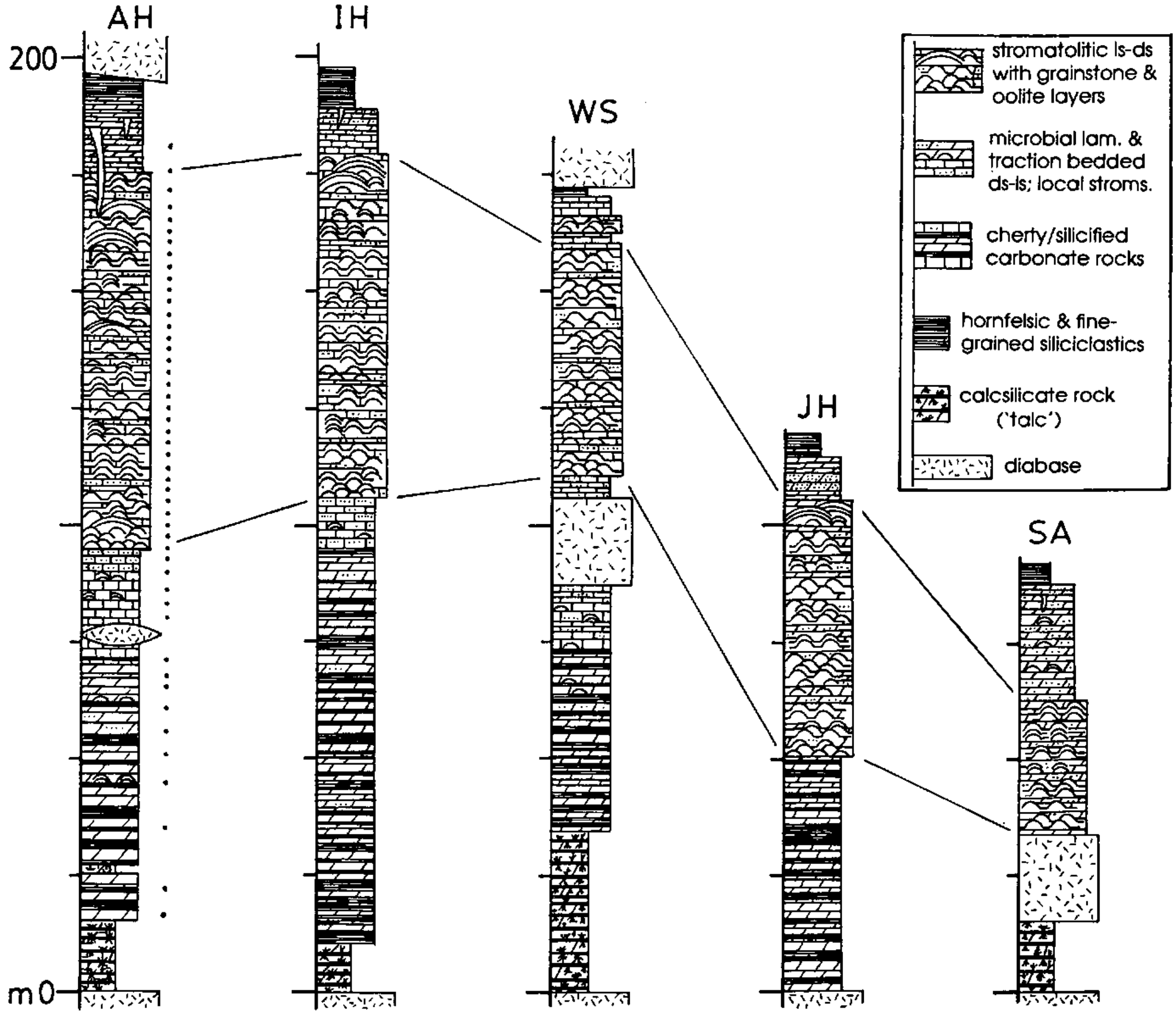


Figure 4. Stratigraphic cross-section using selected sections of the middle member Crystal Spring carbonate platform. Line of section oriented according to paleogeographic relationships resulting from the palinspastic reconstruction shown on Figure 2. Measured sections are: AH-Alexander Hills (Western Talc Mine); JH-Jupiter Hill; IH-central Ibex Hills; SA-central Saratoga Hills; WS-Warm Springs Canyon. Note uniformity of facies from section to section and the systematic northward thickening of both the lower, cyclical carbonate packet and the overlying stromatolitic biostrome. Also note that in many places the biostrome is principally limestone. Dots to the right of the Alexander Hills (AH) section indicate the stratigraphic position of 48 samples collected for C-isotope and trace element analyses. Unpatterned, downward tapering v's in the top of the Alexander Hills, Ibex Hills, and Saratoga Hills sections represent paleokarst (grikes, karstic breccias, geopetal sheet-cracks *etc.*).

the larger diabasic sills. Where such alteration has not totally obscured original sedimentary features, the carbonates display decimeters-thick, traction-bedded, intraclastic packstones and ribbon-rock alternating with thin-bedded microbial laminites (dolomicrites composed of flat to wavy mm-scale laminations; Fig. 5A). These carbonate facies are typically arranged in 1 to 10 m-thick cyclical packets; ribbon-rock dolo(lime)stones are developed above a sharply defined, somewhat scoured base and transitionally pass upward into microbial-laminated dolo(lime)stones (Fig. 5B). The topmost beds in these cycles are generally yellow-gray dolostone and display desiccation features (tepee structures, desiccation cracks, *etc.*). Uncommonly, this facies (particularly where silicification has occurred in a laminae-by-laminae fashion) also can display thin zones characterized by enterolithic-like folds. Larger folds are present locally (encompassing numerous layers and up to a few decimeters in thickness) but these are readily interpreted as soft-sediment deformation (because these facies are not

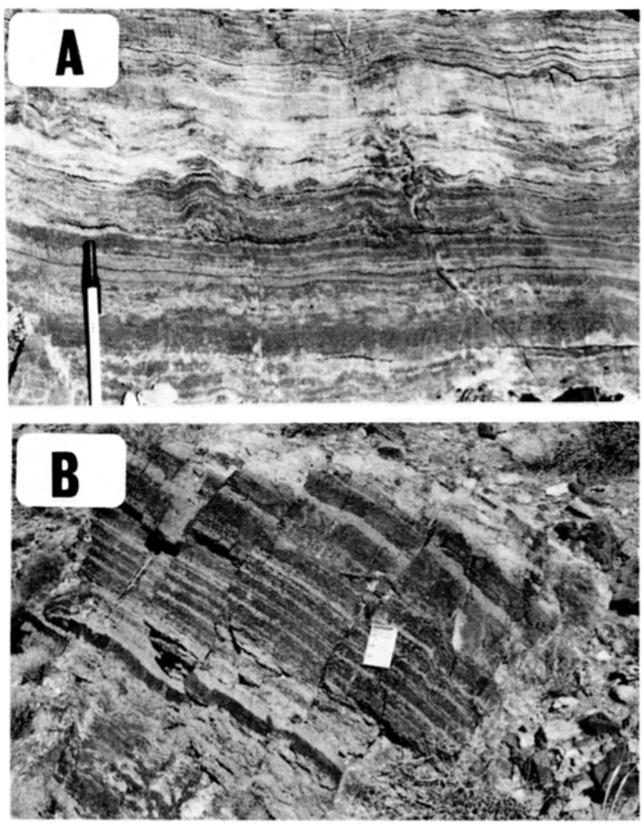


Figure 5. Examples of peritidal carbonate rocks in the lower part of the middle Crystal Spring carbonate platform. **A.** Mixed microbial-laminated and traction-bedded limestone; note fineness of microbial laminae (typically <1 mm thick). **B.** Typical ribbon-rock to flat and wavy microbial-laminated shoaling cycle. Darker colored bands are silicified intervals. Both photographs from the Alexander Hills locality (section AH on Fig. 2).

indicative of steep depositional slopes, are the larger folds seismites?). In places, thin interbeds (< 20 cm thick) of fine sandstone or mudstone are present. These commonly weather in relief and impart a rib-like appearance to the outcrop; they decrease in abundance upward. Locally, within any of the above describe carbonate facies, small (synoptic relief of a few to many centimeters), solitary domal stromatolites can be observed. More rarely, and mostly limited to the ribbon-rock facies, laterally linked heads define stromatolitic biostromes having vertical relief of several decimeters and horizontal extent of several meters to a few tens of meters. Taken together, such facies characteristics typify (*sans* invertebrates) many Phanerozoic carbonate successions interpreted as composed of repeated peritidal shoaling cycles (*e.g.*, Pratt and others, 1992). The cycles in this part of the middle member Crystal Spring are easily interpreted similarly (Roberts, 1982; Prave, unpub. data).

The facies change from the above described peritidal carbonates to the stromatolitic limestone unit typifying the upper part of the middle member Crystal Spring rocks is abrupt. In most localities, a several meters-thick, sharp-based, oolitic-intraclastic grainstone-packstone limestone shoal defines the top of the peritidal carbonate succession (Fig. 4). The stromatolitic unit (Fig. 6) rests with sharp contact on the oolitic-intraclastic limestone and is typified by an assemblage of vertically stacked, branching (*Baicalia*) and non-branching sub-cylindrical heads (*Conophyton*). Head sizes are generally in the many centimeter to several decimeter range and display laterally linked geometry or are separated by centimeter-wide zones of finely laminated dolomicrite as intermound/head fill; in places the fill becomes selectively silicified (Fig. 6B). In bedding plan view, many heads are elongated, implying growth under the influence of tidal currents. Interspersed throughout this dominantly stromatolitic facies are decimeters-thick beds and lenses of intraclastic to oolitic grainstones as well as flat to wavy microbial laminites. Although other workers have implied a vertical cyclicity to these rocks (*e.g.*, Roberts, 1982), my observations based on laterally walking out facies indicate more of an amalgamation of facies; meters-scale stromatolitic biostromes overlap, cap, or are truncated by intraclastic- and oolitic-filled lenses and channels. This facies mosaic is itself abruptly capped by thin-bedded, flat-laminated dolomicrites locally displaying karst; these include clastic-filled grikes (Fig. 7), karstic breccias and pisolites, and a doloclastic-filled (with rare rounded and frosted quartz grains) karst network developed several tens of meters downward into the stromatolitic unit.

Certainly the stromatolitic biostromes are indicative of tidally-influenced (elongated heads) shallow-

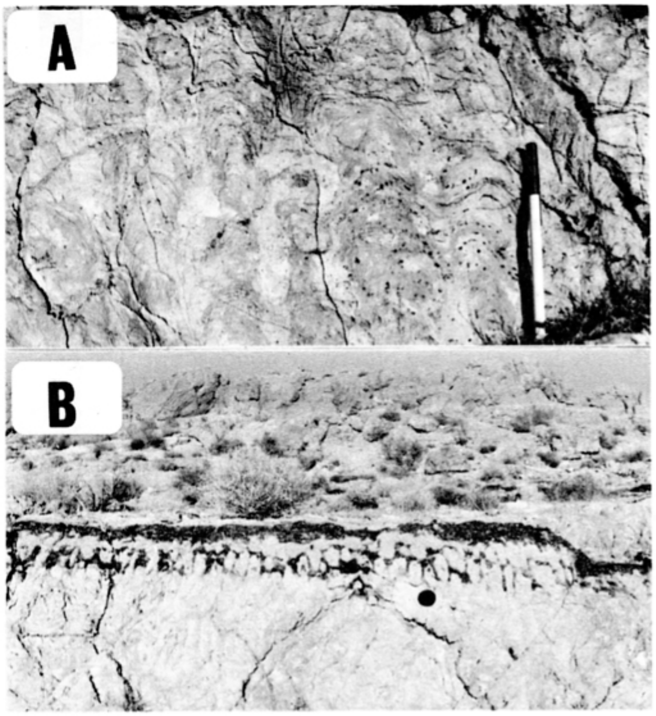


Figure 6. Examples of stromatolitic limestone facies comprising the upper part of the middle Crystal Spring carbonate platform. **A.** Branching sub-cylindrical stromatolite forms (*Baicalia*) and laterally linked heads; this is the basal facies of the stromatolitic unit in the Alexander Hills which rests with sharp contact on underlying peritidal facies. **B.** Conical heads (*Conophyton*) capping a several m-thick stromatolitic biostrome. Intermound fill consists of silicified dolomicrite which highlights individual heads. Alexander Hills (AH on Fig. 2).

Figure 7. Siliciclastic filled grike in flat-laminated dolomicrites at the top of the middle member Crystal Spring carbonate platform. Features such as this one are evidence for paleokarst development signalling the demise of the platform. Ibex Hill locality (IH on Fig. 2).

marine settings. Consequently, the middle member Crystal Spring Formation displays an overall vertical facies transition of a backstepping (transgressive) carbonate ramp (peritidal shoaling cycles to an oolite-intraclastic shoal to shallow marine biostromes). The lateral uniformity of facies thickness and character implies a tectonically stable phase of basinal development in which a relative fall in sea level (karst formation) spelled the demise of this carbonate platform.

BECK SPRING DOLOMITE CARBONATE PLATFORM

Two distinct facies assemblages comprise the 300 to 400 m-thick Beck Spring carbonate platform succession (Fig. 8): (1) a northern assemblage recording a shoaling episode from slope rhythmites, breccias and slumped beds upward to shallow-marine-peritidal oolitic-intraclastic and stromatolitic dolostone (locally limestone); and (2) a southern assemblage of lagoonal/ tidal-flat microbial-laminated dolostones (locally limestone) and distal fluvial/tidal-flat siliciclastic rocks. The northern facies assemblage is commonly considered the 'classical' Beck Spring dolomite, that is, the medium gray, well-laminated dolomite which forms the impressive escarpments typifying middle Pahrump exposures from the Kingston Range westward to the Panamint Mountains (see Fig. 2 for range locations). The southern facies assemblage is best developed in the Saratoga and Saddle Peak Hills.

Previous workers have subdivided the Beck Spring Dolomite into 3 or 4 informal members based principally on the presence or absence of chert or oolites (*e.g.*, the lower cherty, lower laminated, oolite-pisolite, and upper cherty members of Gutstadt, 1968; Marian, 1979; Shafer, 1983). I have chosen to ignore these member constructs and instead focus on the lateral and vertical facies development; one reason being that the proportion and vertical position of chert and/or oolites is quite variable from section to section and does not necessarily yield insights into stratal genesis. Instead, I have defined five vertically arranged facies associations.

The base of the Beck Spring succession (in both the northern and southern facies assemblages) within the depositional framework I have constructed for those rocks is placed at the base of a cross-bedded to planar-laminated quartzitic sandstone to pebbly sandstone unit that varies in thickness from 1 to 15 m (Fig. 8). The basal surface of this sandstone defines a sequence boundary as recognized by: (1) that surface regionally bevels downward through 10-20 m of section; (2) it rests with sharp contact, locally displaying decimeter-scale scouring, on an immediately underlying shallow-marine dolostone (this dolostone is characterized by nodular and bulbous stromatolites, mostly 5-20 cm in diameter, and is informally termed the 'biscuit bed' by Death Valley geologists); and (3) the upper part of this dolostone locally displays a network of paleokarst infilled by sandstone (Mbuyi and Prave, 1992, 1993; Prave 1994, unpub. data). A flooding surface defines the top of the sandstone unit. It is above this surface that the lowermost of the five facies associations defining the northern facies assemblage of the Beck Spring carbonate platform is developed. Note that changes from one facies association to another is transitional.

Beck Spring Dolomite Facies Associations

Northern Facies Assemblage

The lowermost facies association consists of interbedded gray to orange mudstone/shale and graded beds of intraclastic dol(calc)arenites and rudites. The siliciclastic component of this facies association decreases progressively upward until carbonate beds comprise 100% of any given section. The mudstones are mostly thinely laminated but otherwise nondescript. The carbonate interbeds are typically several decimeters in thickness, laterally continuous across the outcrop, have

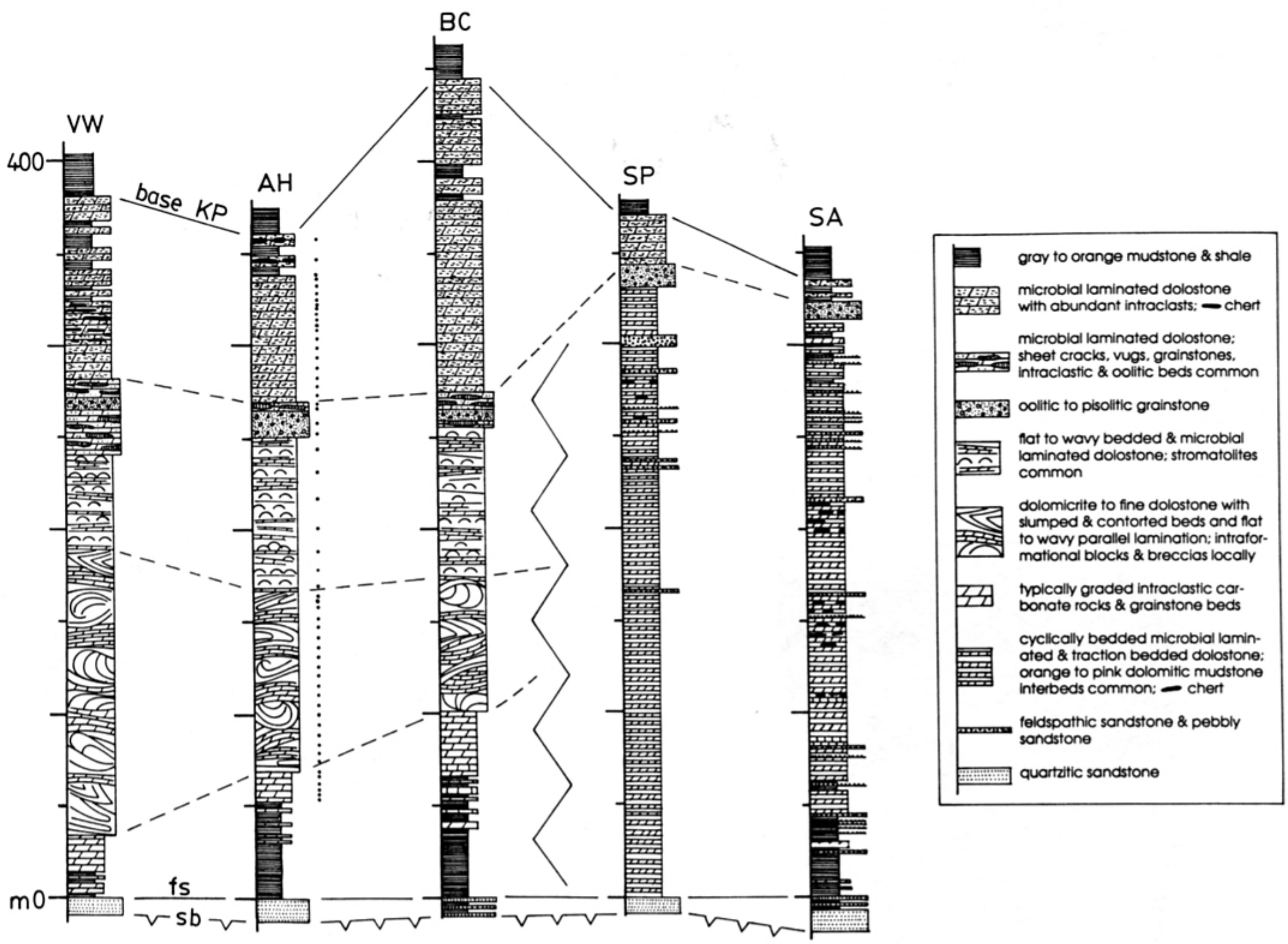


Figure 8. Stratigraphic cross-section of selected sections of the Beck Spring carbonate platform succession. Line of section oriented according to paleogeographic relationships resulting from the palinspastic reconstruction shown on Figure 2. Northern facies assemblage is represented by sections at Virgin Spring Wash (VW), Alexander Hills (AH), and Beck Canyon (BC). Southern facies assemblage is represented by sections in the southern Saddle Peak (SP) and Saratoga Hills (SA). Dots to the right of the Alexander Hills section (AH) indicate the stratigraphic position of 55 samples collected for C-isotope and trace element analyses. Abbreviations: sb-sequence boundary; fs-flooding surface; base KP-base Kingston Peak Fm.

sharp, mostly planar bases, and display grading from lower non-stratified rudites or coarse dolo(calc)arenites up to finely laminated to rippled dolomicrites. In places, rudite beds display wacke(float)stone textures in which large clasts are isolated within a micritic carbonate matrix. Importantly, clast types vary from locally derived rip-up clasts to oolitic, microbial laminated, and geopetal sheet-cracked lithoclasts. Limestone versus dolostone in these rocks appears to be color dependent. Black to dark gray colors typify limestones whereas lighter gray colors typify dolostones; otherwise their facies character is the same.

Based on the development of graded, laterally continuous, coarse beds interbedded with finer mudstones and the lack of any unequivocal shallow marine indicators, this facies association is interpreted as recording downslope sediment gravity flow deposits (turbidites and debrites) into a deep marine basin (at least below storm wave base). The presence of shallow water lithoclasts in the rudites (oolitic and sheet-cracked clasts with geopetal and pendant cements) implies derivation of at least some of this detritus from the cannibalization of a nearby carbonate platform.

The next overlying facies association is a remarkably well-laminated light to medium gray dolomicrite to fine dolostone (hence its characterization by earlier workers as the lower laminated member). Laminae typically are between 0.5 and 2 cm thick. The distinguishing feature of this facies is the presence of meters-thick intervals of slumped and contorted bedding. These intervals are commonly separated by decimeter-thick sets of low-angle, flat to wavy parallel laminae containing rip-up clast breccias (Fig. 9). Tracing of either the slumped or flat-laminated intervals shows they interfinger laterally over distances from a few tens of meters to several hundreds of meters. Rarely, isolated conical to domal stromatolites displaying several decimeters of relief are present within this facies association. In many other places (but principally in lower parts), meters-sized (and smaller) blocks of shallow-marine platform carbonates (oolitic blocks, large stromatolite heads, geopetal vuggy and sheet-cracked microbial laminites, *etc.*) can be observed ranging from single, isolated clasts to chaotically arranged, meters thick rudite lenses.

The presence of contorted beds and the development of monotonously and uniformly thick laminae are used to interpret this facies association as slope rhythmites and breccias containing abundant slump folds. The presence of blocks and olistoliths of shallow-marine platform carbonate rocks similarly imply a foreslope setting. The rarity of stromatolites further supports a deep water interpretation (of course, the background 'rain' of

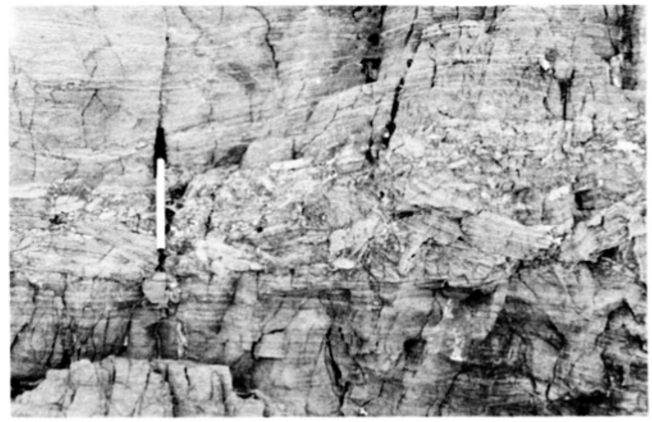


Figure 9. Example of interbedded dolomicritic rhythmites and rhythmite breccias of the slope-foreslope facies association of the northern Beck Spring carbonate platform (note convexity of upper surface of breccia lens). Beck Canyon section (BC on Fig. 2).

carbonate mud producing the rhythmites may well have damped algal growth). It is likely that some of the laminae in this facies is microbial in origin (especially the thinner sets), but most laminae are too thick and lack the wrinkled, crinkled fabric so typical of other microbial laminites throughout the Pahrump Group.

The third facies association recognized in the northern facies assemblage gradationally overlies the slumped beds and rhythmites. It consists of flat- to wavy-laminated, fine dolostone and microbial-laminated dolomicrite. Slumped intervals are rare whereas biostromes of domal and conical stromatolites are common. Rip-up intraclastic beds, torn-up and jumbled stromatolites, and oolitic grainstones (Fig. 10A) imply a relatively high-energy setting (the oolite-pisolite member of earlier workers). These facies are everywhere overlain by a 10 to 40 m-thick mosaic (comprising the fourth facies association) of oolite-pisolite, traction-bedded grainstones-packstones, microbial laminites, domal and conical stromatolite biostromes and, most diagnostically, a sheet-cracked and brecciated dolostone (Fig. 10B). This latter facies displays geopetal fabrics, isopachous and pendant cements, and paleokarstic breccias. Although rare, any of the above described facies can occur locally as limestone.

The lithological character of these facies associations indicates deposition in a shallow marine, relatively high-energy setting. Placed within the overall vertical facies transition described above (Fig. 8), these rocks represent a progradational cycle from basinal turbidites and debrites, to slope rhythmites and slumps and foreslope breccias upward to a rimmed shelf of shallow marine oolitic shoals, grainstones, intraclastic beds, and stromatolitic biostromes. The topmost beds of this 200 to 300 meter thick shoaling succession contain evidence

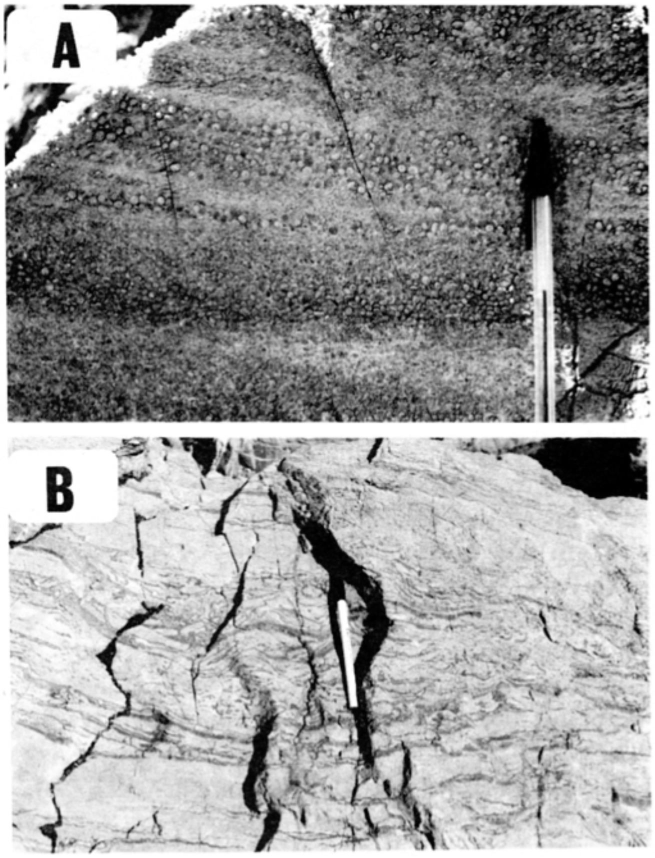


Figure 10. Examples of platform rim facies of the northern Beck Spring carbonate platform. A. Cross-bedded oolitic-pisolitic grainstone; Alexander Hills section (AC on Fig. 2). B. Sheet-cracks, geopetal structures, pendant cements, and paleokarstic brecciation with dolomicritic interfill; Beck Canyon (BC on Fig. 2).

for paleokarst, but it is important to note that nowhere was extrabasinal infill of paleokarstic features observed---all detritus appears to be intraformational and micritic to lithoclastic in nature. It is this oolite-pisolite and sheet-cracked facies interval which is the first unit that can be traced into the southern facies assemblage (the Saratoga and Saddle Peak Hills sections; Figs. 2 and 8). In fact, it is this unit that Zempolich and others (1988) studied and obtained isotopic and trace element values reminiscent of Phanerozoic ocean chemistries. This implies that expansion of the platform rim occurred in both landward and basinward directions during its penultimate development.

The fifth facies association to typify the Beck Spring carbonate platform, in *both* northern and southern facies assemblages (Fig. 8), consists of an amalgam of microbial laminated dolostones with abundant intraclastic rip-up beds, traction-bedded packstones, and mixed oolitic grainstone-packstone lenses. It is within this unit that medium to dark gray chert lenses and nodules are present (hence its characterization by earlier workers as the upper cherty member). Beds are typically many centimeters to several decimeters thick. Small, domal to sub-cylindrical, branching and non-branching stromatolites (*Baicalia* and *Conophyton*) are common. Locally, desiccation features such as mud-chip breccias and mudcracks are developed, but these have been observed only in the lowermost units of this facies association. In an apparent transitional facies change into the overlying Kingston Peak Formation, interbedded intervals of nondescript, laminated to rippled, gray to orange mudstone become abundant upward (Fig. 8).

These facies represent an expansion of more open-marine settings across the entire rimmed platform (both northern and southern facies assemblages). They are inferred to record transgressive overlap and high-energy (storms?) reworking of the platform rim. The progressive upsection increase in interbedded mudstones indicates that not only was the platform transgressed, it was also becoming blanketed by siliciclastic detritus. This detrital blanket (represented by the mudstones and fine sandstones of the lower member Kingston Peak Formation) eventually overwhelmed carbonate production.

Southern facies assemblage

The character of the southern facies assemblage of the Beck Spring carbonate platform is quite distinct from those described above. Two facies associations characterize this assemblage. The most dominant facies association by far is quasi-cyclical to acyclical packets of microbial-laminated dolomicrite (locally occurring as dark gray limestone) with abundant desiccation features (Fig. 11A; desiccation-chip breccias, tepee structures, desiccation cracks, strongly crinkled and contorted laminae, *etc.*), traction-bedded dolostone pack-wackestones, dolostone ribbon-rock, and gray to orange dololutites, dolomitic shales, and mudstones. It is not uncommon to find rounded, frosted quartz sand grains sparsely disseminated throughout any of the carbonate rocks. Packet thicknesses are variable and range between several decimeters up to 10 meters or more. Randomly interspersed throughout these rocks are erosive, sharp-based, poorly sorted, flat-laminated to cross-bedded feldspathic sandstones and pebbly sandstones (Fig. 11B). Clasts are rounded to angular and include dolostone derived from subjacent facies as well as extrabasinal clasts of quartzite and gneiss. Clast diameters (of either the carbonate or quartzite-gneiss clasts) are between 1 and 20 cm. Beds range from veneers one-grain layer in thickness (these mostly occur on corroded and iron-stained surfaces at the top of carbonate packets) up to amalgamated layers several meters thick. Lateral continuity of these beds is typically less than 1 to 2 km. Paleocurrent data from this

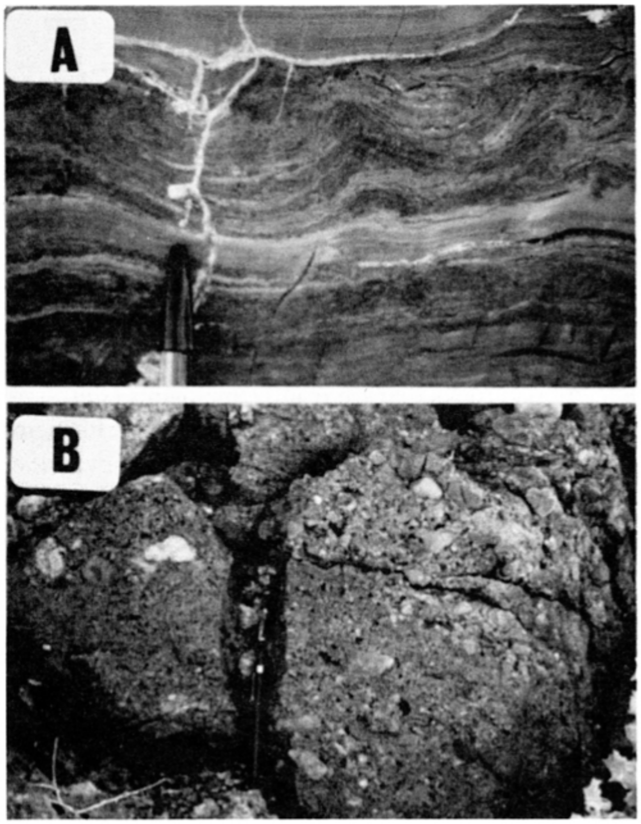


Figure 11. Examples of facies typical of the southern facies assemblage of the Beck Spring carbonate platform. **A.** Microbially laminated dolomicrites; note contorted laminae in center, development of overthrust limbs in tepee structure to the right, and erosional truncation of folds and contorted laminae by overlying laminae (southern Saratoga Hills section; SA on Figs. 2 and 8). **B.** Pebbly arkosic sandstone facies (southern Saddle Peak Hills section; SP on Figs. 2 and 8).

facies consistently yield a northerly direction of sediment transport (Fig. 12).

Combined, these two facies associations are interpreted as recording deposition in protected lagoonal/back-platform and tidal-flat settings commonly experiencing desiccation. Carbonate mud deposition (dolomitic marls, mudstones, and microbial laminites) predominated with occasional influx of coarser carbonate detritus derived from the platform rim (storm-emplaced oolitic-intraclastic packstones-grainstones). Similarly, coarse feldspathic detritus was infrequently flushed into this setting most likely by distal fluvial distributaries draining a quartzofeldspathic basement source area exposed to the south-southwest.

In summary, the lateral and vertical facies trends of the Beck Spring carbonate platform record the overall development of a rimmed shelf at the latitude of the Kingston Range and northward (Figs. 2 and 8). The detrital apron shed from and fringing this rim (the slope rhythmites and breccias) formed the substrate for the platform to prograde. It is interesting to note that the combined thicknesses of the basinal turbidite/debrite and slope-foreslope facies from section to section are quite similar (Fig. 8; the differences in thicknesses between these facies simply represent the degree of lateral mantling of the basin floor by the slope-foreslope apron). This might very well indicate that accommodation space had to be filled to a particular paleobathymetric depth before the stromatolitic-oolitic rimmed shelf could nucleate. Landward of the rimmed platform (in the vicinity of the Saddle Peak and Saratoga Hills and southward; see Figs. 2 and 8), quieter lagoonal/back-platform carbonate muds were deposited and microbial communities formed. These often experienced desiccation and blanketing by fluvially derived fine to coarse siliciclastics.

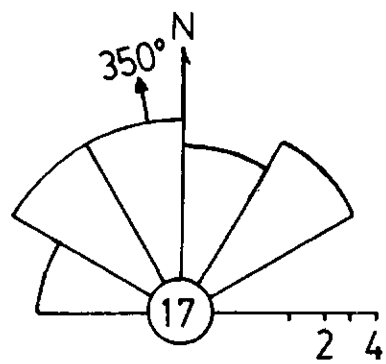


Figure 12. Equal area paleocurrent rosette constructed from measurements of trough cross-bed axes developed in arkosic sandstones in the southern Saratoga and Saddle Peak Hills (sections SA and SP on Figs. 2 and 8). Class interval is 30°; circled number indicates readings.

It is curious that the lagoonal/back-platform southern facies assemblage is thicker than the slope-rimmed shelf naorthern facies assemblage (Fig. 8). Given the lack of a finely-resolved chronostratigraphic framework, the most circumspect inference that can be drawn is that the rate of carbonate production and siliciclastic influx was more or less similar to the rate of generation of accommodation space (at least until transgressive overlapping by the oolite-pisolite-sheet-cracked facies occurred). This suggests that tectonic influences were driving accommodation space generation. At present, I can only speculate as to the genesis of such tectonism, but suffice it to say that such an inference is supported by: (1) the coarse, arkosic nature of the pebbly sandstones in the southern facies assemblage; and (2) that immediately upsection is the clearly tectonically influenced Kingston Peak Formation. Nevertheless, the close of Beck Spring time is marked by an overall increase in the rate of generation of accommodation space (transgressive drowning) as well as an increase in the flux of siliciclastics (interbedded mudstones in the top part of the Beck Spring succession). Combined, they resulted in the demise of the Beck Spring rimmed carbonate platform.

One final issue needs to be addressed. Recently, Horodyski and Knauth (1994) reported the occurrence of microbial fossils developed on paleokarst at the top of the Beck Spring Dolomite from a section near Jupiter Hill (JH on Fig. 2). The interpretation I have presented for the Beck Spring platform indicates collapse and drowning, rather than exposure for the topmost part. Resolution of these contrasting interpretations is important because of the implications involved for biospheric evolutionary trends. In my mind, the answer is clear. The location that Horodyski and Knauth sampled is along a faulted margin of a Precambrian basin developed *during Kingston Peak Formation time*. The underlying Pahrump units were uplifted, exposed, and eroded along that margin (Wright and others, 1976) and it was then, not at the close of Beck Spring time, that the paleokarst developed. Microbes may very well have inhabited a paleokarst surface on the Beck Spring Dolomite, but it is of Kingston Peak age.

SUMMARY AND CONCLUSIONS

The Mesoproterozoic middle member Crystal Spring and Neoproterozoic Beck Spring carbonate platforms display lithofacies and stratigraphic frameworks that can be compared to Phanerozoic ones. The 100-200 m-thick Crystal Spring rocks contain meters-scaled peritidal shoaling cycles upward to a transgressive ramp facies assemblage characterized by an interwoven mosaic of stromatolitic biostromal 'reefs' and oolitic-grainstone-intraclast beds. The demise of this carbonate ramp is marked by paleokarst subsequently followed by an influx of siliciclastics. In contrast, the thicker (up to 500 m) Beck Spring carbonate platform records the progradation of a rimmed-shelf replete with slope and foreslope rhythmites and breccias, stromatolitic biostromal 'reefs,' and lagoonal/back-platform facies. Its demise was due to transgressive drowning and subsequent blanketing by fine siliciclastics.

FIELD TRIP STOPS

The field trip will begin and end in Las Vegas (the official start is at the loading dock of the Excaliber Hotel-Casino; the official end will be at McCarran International Airport). The following is a brief description of the field trip stops and route. We will focus on the stratigraphic development and facies character of the Mesoproterozoic middle member Crystal Spring and Neoproterozoic Beck Spring carbonate platforms. The main theme will be for you to recognize features in these Precambrian rocks that are readily analogous (*sans* biomineralizing invertebrates) to those of their Phanerozoic counterparts. Measured sections, outcrop overview photos, and simplified geologic maps of each of the field trip stops are included at the end of this discussion.

DAY 1

Depart from the loading dock of the Excaliber Hotel-Casino at 7:00 a.m. and proceed to I-15. Head west on I-15 (toward Los Angeles) for ~60 miles to Cima Road Interchange. Exit at interchange and head north along Kingston Rd (Cima Rd becomes Kingston Rd north of the I-15 interchange) for ~12.5 miles where Kingston Rd splits. Follow the main road (Excelsior Mine Rd, the slightly left-hand fork) towards the Kingston Range (large range directly in front of you) for about another 15.5 miles.

STOP 1: Overview of Pahrump stratigraphy and basin

This stop is an overview stop to point out the pertinent features of the Pahrump Group and its basinal margins (it also allows you to stretch your legs a bit). It is a good introduction to Basin and Range physiography and the style of Neogene extensional tectonics.

Continue northwest, over Tecopa Pass and down through Beck Canyon to Stop 2 at its western mouth (total travel distance from Stop 1 to 2 is ~6.5 miles).

STOP 2: Beck Canyon Dolomite

This is a wonderfully exposed section of the Beck Canyon Dolomite (Figs. 13 and 14); unfortunately it is over 300 m of vertical relief, but numerous gullies and washes permit a fairly straightforward access to the top. The rubbly and ribby exposures low on the slope are the interbedded mudstones and carbonate turbidites and debrites which represent the deeper basinal portion of the carbonate platform (note that some of the darker gray beds in this succession are limestone). These pass upward to the main cliff-like exposures of the Beck

Spring which consist of foreslope and slope breccias, slumps and rhythmites upward to shallow-marine oolitic-grainstone shoals and stromatolitic biostromes of the platform rim. The prominent light gray band near the top of the cliff is the sheet-cracked and microbial-laminated rim top; essentially you are looking at the exhumed relief of the entire carbonate platform! On top of this band, the Beck Spring is transgressively overlapped by microbial laminites and rip-up beds and eventually blanketed by the finer siliciclastics of the lower member Kingston Peak Formation. Our traverse will take us to this contact (note that the topmost Beck Spring

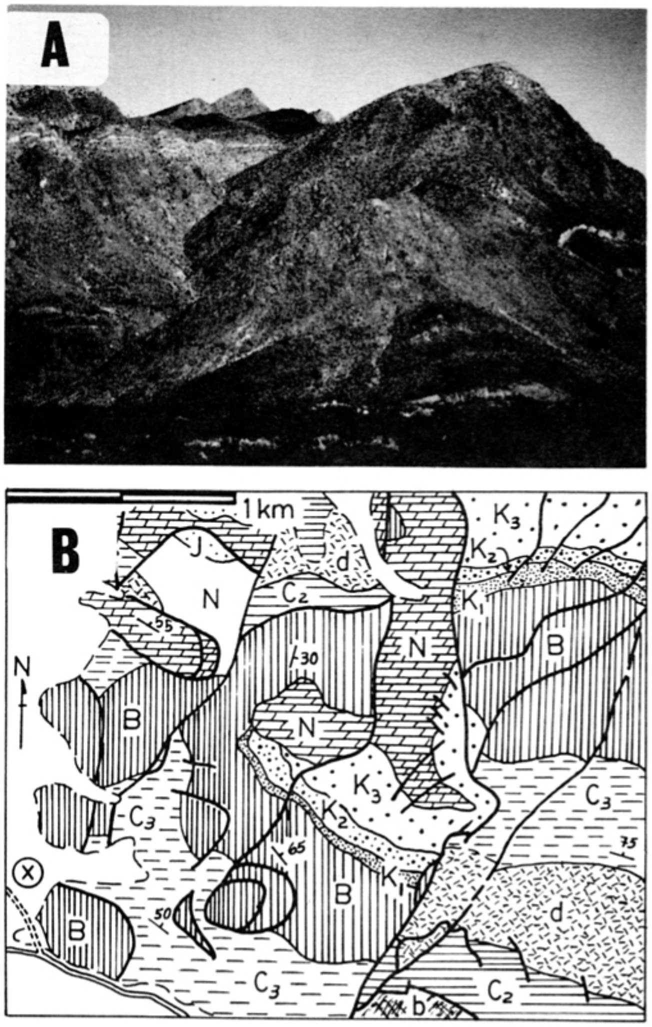


Figure 13. **A.** Photograph of Stop 2, Day 1: Beck Spring Dolomite at western end of Beck Canyon (BC on Figs. 2, 3, and 8). **B.** Simplified geologic map of the Beck Canyon area (unpub. mapping by Troxel, Wright, McMackin, and Prave). Circled x marks van stop. Abbreviations: b-basement; B-Beck Spring Dolomite; $C_{1,2,3}$-lower, middle, upper members Crystal Spring Fm; d-diabasic sill; J-Johnnie Fm; $K_{1,2,3}$-lower, middle, upper members Kingston Peak Fm; N-Noonday Dolomite.

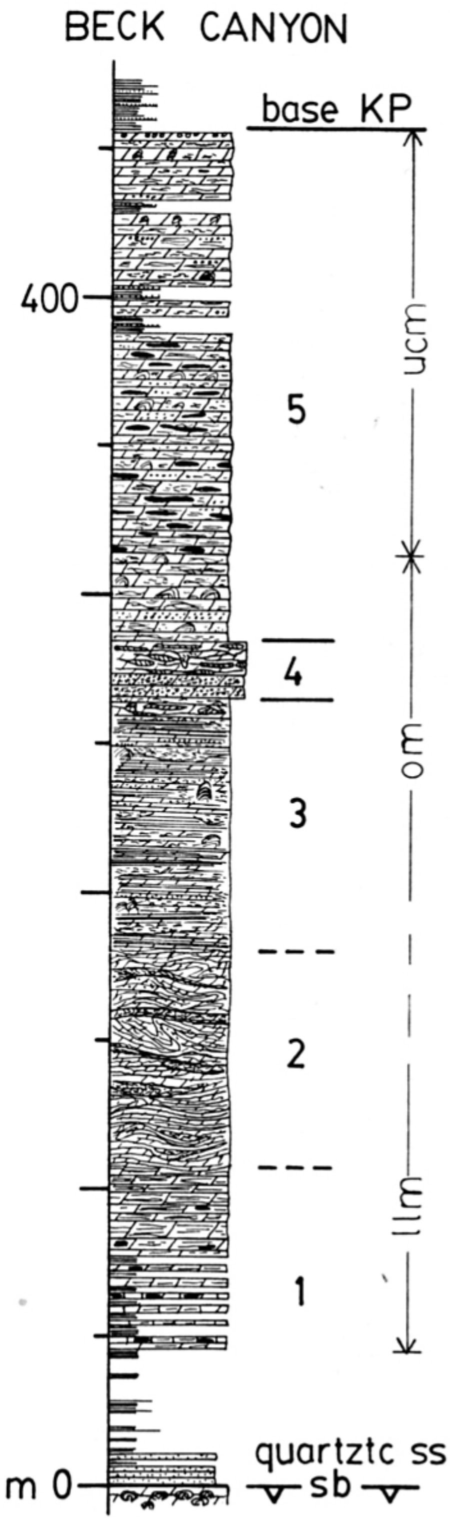
bed is oncolitic (*Girvanella*?)). Observations of interest include: (1) abundant slumped intervals in slope facies; (2) local presence of talus blocks derived from the platform rim; (3) thickness of laminations in the shallow-marine microbial laminites versus the slope rhythmites---can you convince yourself of their geometrically distinct character?; (4) excellent examples of isopachous, pendant and meniscus cements, geopetal structures, paleokarst dissolution and brecciation, and oolite-pisolite along the top of the platform rim. The top of this exposure provides a marvelous overview of the field trip area and we will take advantage of this setting for our post-traverse discussion.

Carefully go back down the Beck Spring escarpment to the vans and then on to the Alexander Hills for Stop 3. Continue down the road out of Beck Canyon (now known as Furnace Creek Rd) for ~6.5 miles. Turn left onto Western Talc Rd and follow this (for ~3.5 miles) to the abandoned Western Talc Mine.

STOP 3: middle member Crystal Spring Fm

This exposure is one of the most complete, easily accessed middle Crystal Spring outcrops anywhere in the southern Death Valley region (Figs. 14 and 15). We will start our traverse at the diabase sill-calcsilicate ('talc') contact and proceed upsection. The two main facies assemblages of this carbonate platform are readily recognized: the cherty peritidal dolostone cycles comprise the lower, banded half of the outcrop whereas the stromatolitic bioherms ('reefs') and intraclastic-grainstone-oolite limestones form the steeper slopes in the top half of the exposure. The light-gray horizon separating these two facies is an oolitic-grainstone shoal. The obvious vertical zones of meters-wide brownish-stained rocks in the cliffy limestone exposures are minor fault zones. Observations of interest are: (1) the similarity in facies character of the meters-scale peritidal shoaling cycles to those amply described from younger rocks; (2) the wonderful examples of branching (*Baicalia*) and non-branching (*Conophyton*) stromatolites that comprise the biostrome; (3) the overall increase in stromatolite head size in the upper 20 m; (4) the presence of paleokarst in the topmost part of the platform; (5) bedding plane views on the dipslope side (note how stromatolites are elongated). We will meet on the top of the ridge for a discussion of our traverse and for me to point out some pertinent features of the Pahrump Group basinal geometry in the southern Nopah Range to our north. This position will also provide an excellent view back to our Beck Canyon traverse. From here we will proceed about halfway down the dipslope to critically evaluate the evidence for and interpretation of paleokarst on several of the bedding surfaces.

We will return to the vans for an ~20 mile ride through the scenic hamlets of Tecopa and Tecopa Hot Springs to Shoshone (we're staying in the Shoshone Motel). We will meet John Cooper's and Martin Keller's field trip (Ordovician carbonates) for a joint dinner (included in your field trip costs) and slide show.



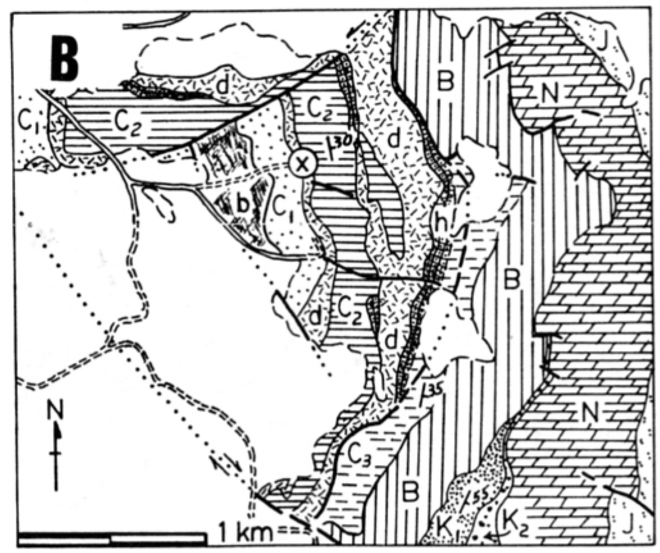


Figure 15. **A.** Photograph of Stop 3, Day 1: middle member Crystal Spring carbonates in the Alexander Hills (AH on Figs. 2, 3, & 8). **B.** Simplified geologic map of the Alexander Hills (mapping by Wright, 1957; unpub. mapping by Prave). Circled x marks van stop. Abbreviations same as those on Figure 13B with the addition of: h-hornfelsic ('cherty') rocks.

Figure 14. Measured section of Beck Spring Dolomite at Beck Canyon (BC on Figs. 2, 3, and 8). Numbers refer to facies associations described in text: 1- deeper basin: interbedded mudstone and carbonate turbidites and debrites; 2-slope-foreslope: dolostone rhythmites, slumps and breccias; 3-4 shallow-marine shoal and platform rim: microbial laminites, stromatolitic biostromes, grainstone-intraclastic beds, pisolite-oolite beds, and sheet-cracked dolostone with abundant pendant-meniscus-isopachous cements and paleokarst; 5-transgressive shallow-marine: microbial laminites and rip-up beds interbedded with increasing proportion of mudstone upward. Abbreviations: base KP-base of Kingston Peak Fm; b-sequence boundary. Informal members of previous workers: llm-lower laminated member; om-oolitic member; ucm-upper cherty member.

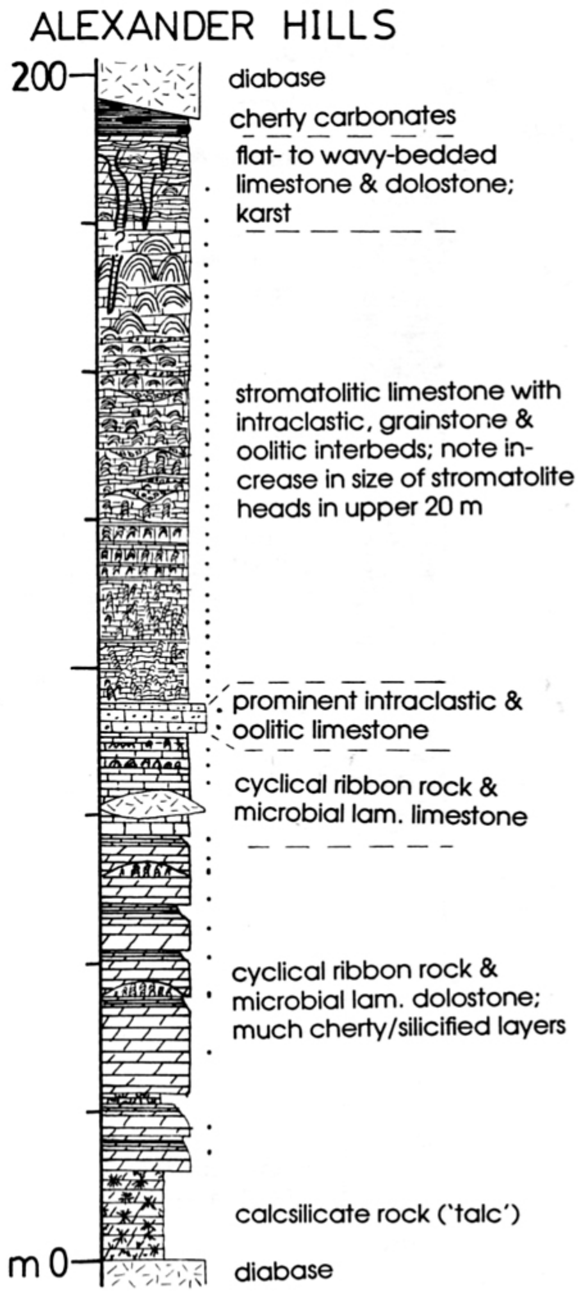


Figure 16. Measured section of the middle member Crystal Spring carbonate rocks in the Alexander Hills (AH on Figs. 2, 3, and 4).

DAY 2

After check-out and breakfast (breakfast and a box-lunch are included in your field trip costs), we will depart Shoshone at 7:00 a.m. We'll proceed south (towards Baker) on Highway 127 for ~19 miles (over Ibex Pass) and turn right onto Ibex Springs Rd (at the Relay Station). After ~2.7 miles we will turn south (left) down Ibex Wash for the ~6.5 mile drive to Saratoga Springs and Stop 1.

STOP 1 (Day 2): Traverse of the Crystal Spring-Beck Spring rocks

We are now in Death Valley National Park where collecting of specimens and hammering of rocks is not permitted---please obey these Park Service rules. This is an ecologically interesting area with the touristic Saratoga Springs and pupfish. Additionally, petroglyphs are chiseled into the diabase next to the parking area. Note that the view into southern Death Valley from this perspective is an exceptionally aesthetic one.

This is our only stop of the day (Figs. 17, 18, and 19), so we can maintain a reasonable pace. Unfortunately, the 1.08 Ga diabase sills obscure much of the middle Crystal Spring carbonates but exposures adjacent to the car park and along our traverse should convince you of the similarity to facies we examined yesterday in the Alexander Hills. Such is not the case for the Beck Spring rocks. We are now in the southern facies assemblage represented by lagoonal/back-platform and tidal-flat settings. Our goal will be to traverse these rocks noting: (1) evidence for desiccation (tepee structures, intensely crinkled-wrinkled laminae, *etc.*); (2) abrupt influx of coarse, arkosic lenses--what is their paleoenvironmental and tectonic significance?; (3) nature of the basal sequence boundary defining the beginning of 'Beck Spring' deposition; (4) the oolite-pisolite unit at the top of the section; it is gray dolostone here, but along the outcrops across the wash to our north it is a dark gray limestone; (5) the facies character of the top Beck Spring bed at the Kingston Peak contact and the character of the Kingston Peak 'flysch.' Also note that we will traverse the upper member Crystal Spring, so we can discuss the evidence for a major unconformity at its base as well as compare-contrast its facies character with that of the Beck Spring rocks.

We will eat a box-lunch on the outcrop and should be back at the vans by no later than 2:00 p.m. for our return drive to Las Vegas (~125 miles from this point).

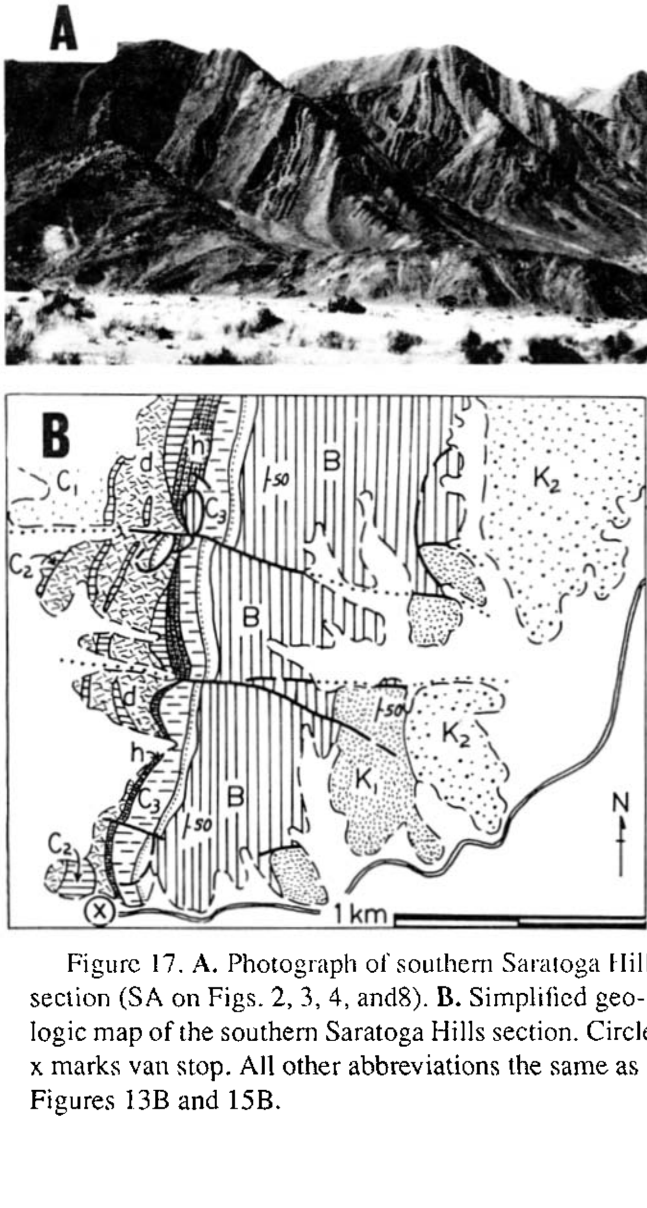


Figure 17. **A.** Photograph of southern Saratoga Hills section (SA on Figs. 2, 3, 4, and8). **B.** Simplified geologic map of the southern Saratoga Hills section. Circled x marks van stop. All other abbreviations the same as Figures 13B and 15B.

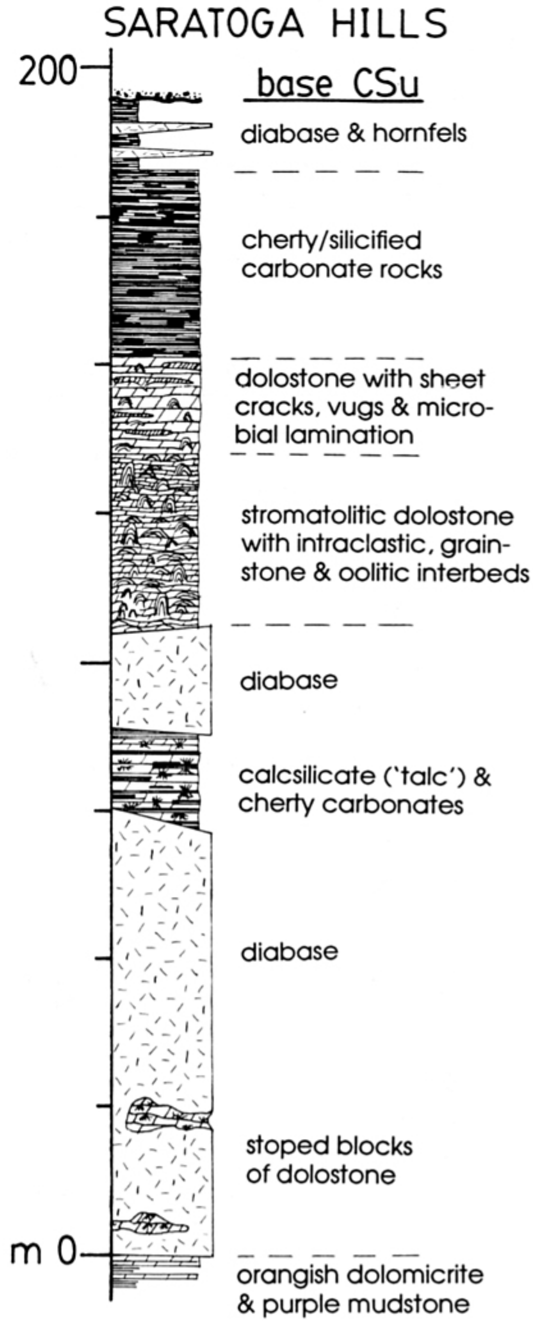


Figure 18. Measured section of middle member Crystal Spring rocks in the central Saratoga Hills (SA on Figs. 2, 3, and 4). CSU: upper Crystal Spring Fm.

ACKNOWLEDGEMENTS

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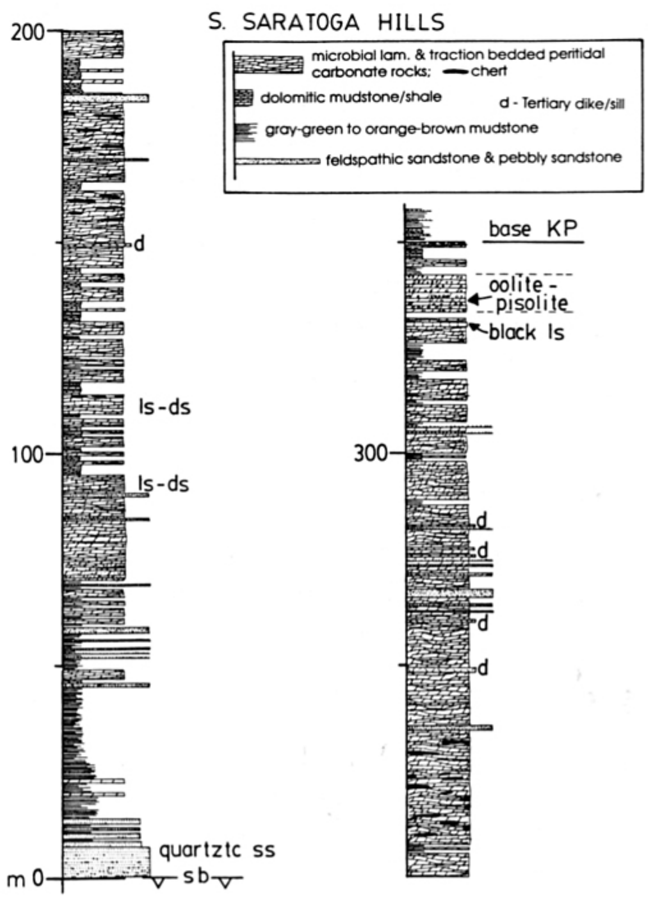

Figure 19. Measured section of Beck Spring Dolomite in the southern Saratoga Hills (SA on Figs. 2, 3, and 8). sb-sequence boundary; ls-ds-mixed limestone and dolostone; KP-base of Kingston Peak Fm.

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