Field relationships throughout the southern Death Valley region of CA require the Horse Thief Spring Formation to be older than the 1.1 Ga Crystal Spring diabase.

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Abstract

Mahon et al (2014) renamed the upper member of the Mesoproterozoic Crystal Spring Formation as the Horse Thief Spring Formation (HTS), claiming its age to be <787 Ma on the basis of a few detrital zircons. This prompted a fresh look at the field relationships of the HTS and the Crystal Spring diabase because of the importance of their ages in deciphering the history of the Rodinia supercontinent (Calzia et al, 2015). We verify that throughout the region these diabase sills produced metamorphic aureoles in the HTS where they intruded adjacent to or into it. Inclusions of shale, siltstone and carbonate fragments from the HTS, sometimes folded, dismembered and/or clearly having mixed with the diabase magma, are widespread. Chilled diabase contacts are present where the proposed HTS age requires an unconformity. In the Jupiter Hill area of the northeastern Kingston Range, ~8 km east of the HTS type locality, a diabase sill which intruded the HTS, picking up numerous HTS inclusions in the process, yields a baddeleyite age of 1.1 Ga (Rämö et al, 2016) in agreement with the 1.1 Ga age for a sill in the northwest Kingston Range. The Saratoga Springs sill (1.07 Ga age) underlies the HTS reference section and detrital zircon sample location of Mahon et al. Apophyses from this sill occur in the conglomerate at the base of the HTS, and its contact metamorphic aureole extends into the HTS. In the southeastern Panamint Range, the Timmy deposit has a dramatic 450 m long and 30 m thick finger of HTS extending into a body of diabase. This and additional evidence that the HTS must be older than 1.1 Ga is documented with GPS-located photographs, maps, and a regional fence diagram summarizing the Mesoproterozoic stratigraphy.

Discussion

Simplified descriptions of the Crystal Spring Formation refer to diabase as intruding the lower and middle units of the formation, neglecting the well-known fact that the sills also occur in the upper Crystal Spring Formation (e.g. Wright, 1968, and see fence diagram). Arguments that these upper sills could be a separate magmatic event from the lower ones do not hold up against the evidence. The sills are indistinguishable geochemically (Hammond, 1986), and within the Kingston Range the upper and lower sills are essentially the same age, with the reported age for the upper sill being slightly older (see Jupiter Hill images).

The conglomerate at Saratoga Spring that Mahon et al (2014) claim was deposited on a regional unconformity is but the upper one of several closely spaced, similar conglomerates at that location. Conglomerates occur at the base of the upper Crystal Spring Fm (renamed Horse Thief Spring Fm by Mahon et al) at southwestern exposures of the unit (e.g. northern Avawatz Mountains and see Timmy deposit images) but are lacking to the northeast, most conspicuously at the type section in the Kingston Range. If the Horse Thief Spring Fm were younger than the diabase and there were a significant unconformity, the upper surface of the diabase would be eroded everywhere it is overlain by the Horse Thief Spring Fm. Instead chilled diabase and contact metamorphic aureoles are present where this contact can be observed (Markley road and Saratoga Spring images). Thus the conglomerates and angular unconformities in the southwestern part of the region are reasonably explained by Maud (1983, p. 35) as features formed close to a basin margin, not as regional markers.

Through the years, there have been informal reports of diabase clasts in the upper Crystal Spring Fm conglomerates, but none of the authors have seen diabase clasts in the conglomerates or in thin section. Instead there are abundant fragments (see Jupiter Hill images) plus large segments of individual beds (see Beck Canyon images) of the upper Crystal Spring Fm enclosed in the diabase.

These lines of evidence combine to provide a very compelling case that the upper Crystal Spring Fm must be older than1.1 Ga. The few anomalously young detrital zircons presented as the reason for claiming a maximum depositional age of <787 Ma for the Horse Thief Spring Fm and the existence of a major regional unconformity are inadequate evidence. Calzia et al (2015) concluded that the young detrital zircon ages were due to lead loss in response to the complex magmatic and tectonic history of the Death Valley region.

References

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Rämö, O.T., Calzia, J.P., Mänttäri, I., Andersen, T., Lahaye, Y., Lehtonen, M., 2016, Mesoproterozoic diabase in Death Valley, California: *in* Staboulis, S., Karvonen, T., Kujanpää, A., (eds), Abstracts of the 32nd Nordic Geological Winter Meeting, 13th-15th January 2016, Helsinki, Finland. Bulletin of the Geological Society of Finland Special Volume, p. 205-206.

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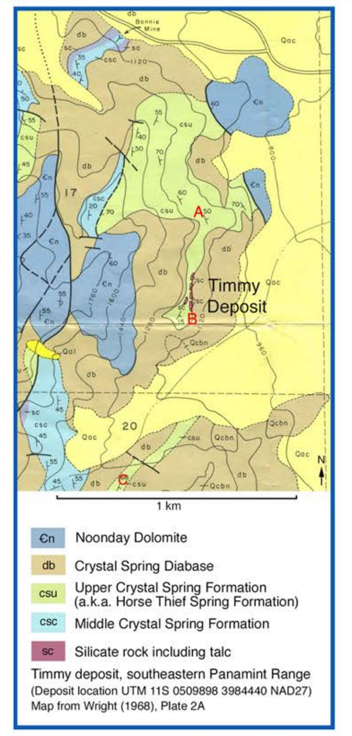
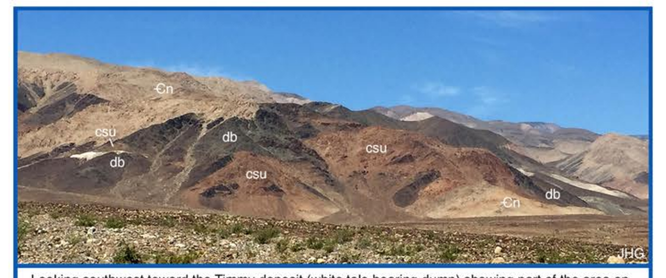
Timmy deposit, southeastern Panamint Range



Timmy deposit, southeastern Panamint Range (Deposit location UTM 11S 0509898 3984440 NAD27) Map from Wright (1968), Plate 2A

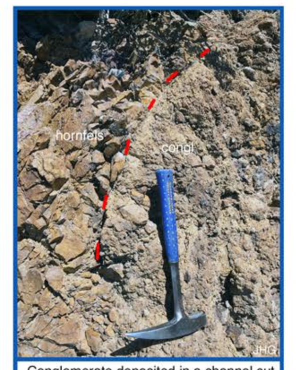


Looking southwest toward the Timmy deposit (white talc-bearing dump) showing part of the area on the map. The diabase-enclosed finger, composed mostly of dolomite of the upper Crystal Spring Formation (csu, a.k.a. Horse Thief Spring Formation), hosts the talc deposit and is 450 m long with an average thickness of 30 m (Wright, 1968, p. 73). The finger connects to the large exposure of csu which includes small diabase intrusions and their erosion-resistant metamorphic aureoles.

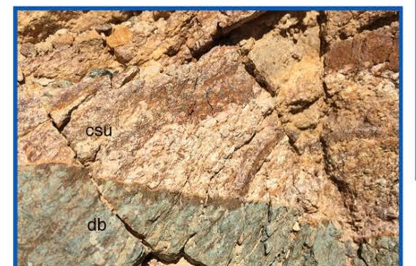
Upper Crystal Spring Formation with diabase intruded above and below as shown at C on the map. Telephoto view to the south from the Timmy deposit.

Diabase sill in csu at map location A. Star in image 1 shows location of hammer in 2 and 3. Sill is <2 m thick, fine-grained and foliated with abundant apatite crystals, a signature characteristic of the Crystal Spring diabase. Black hornfels and dolomite marble of the contact aureole are more erosion resistant than their unmetamorphosed equivalents.

Stratigraphic up direction is downslope. UTM location is 11S 0510059 3984914 NAD27.

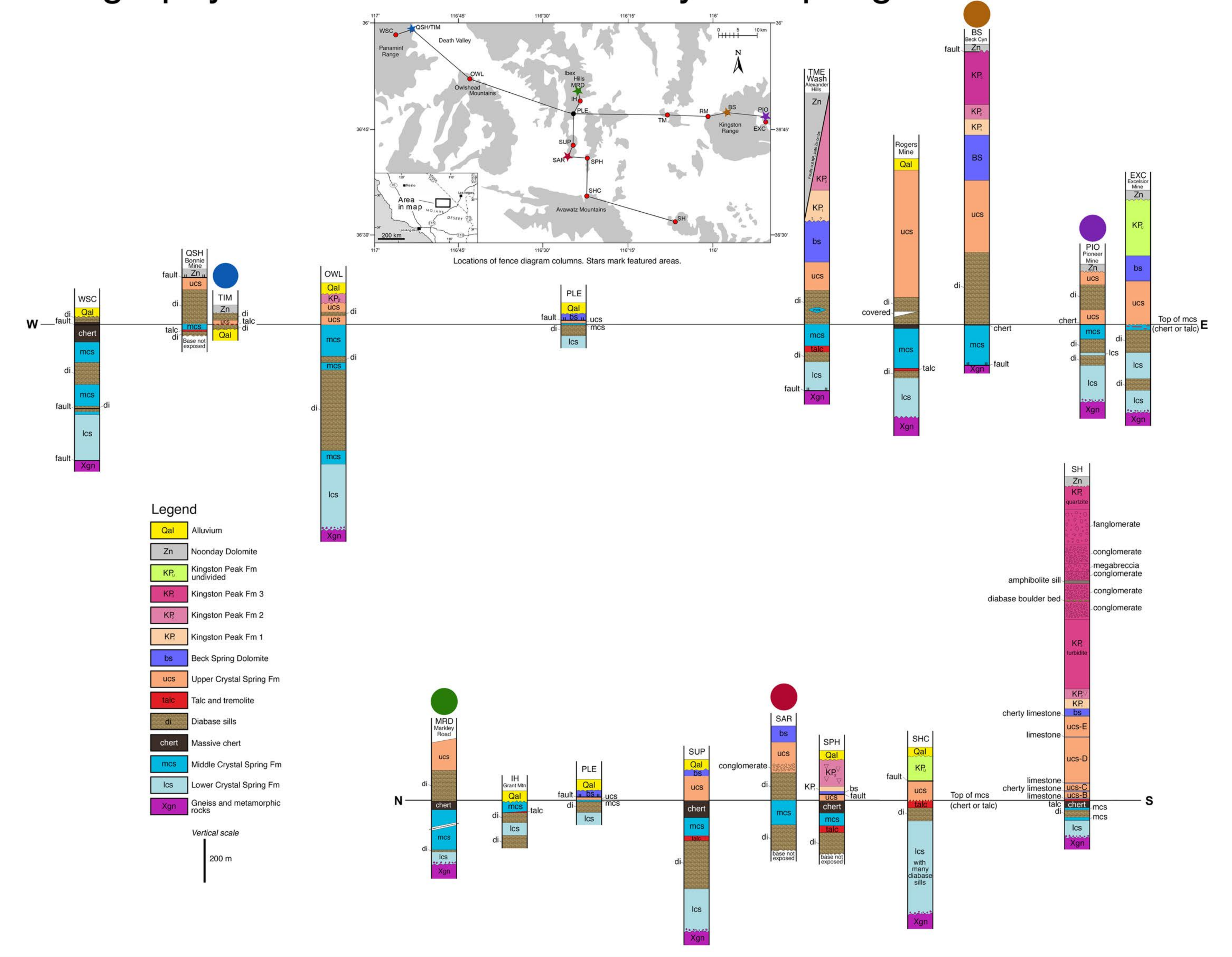


Conglomerate deposited in a channel cut in hornfels within the contact aureole of diabase intruded above and below it. Conglomerate at the base of the Horse Thief Fm is restricted to its western exposures. Coarse sandstone successions define the base of the type section in the Kingston Range to the east. Near B on map. View to north from UTM 11S 0509721 3984464 NAD27.

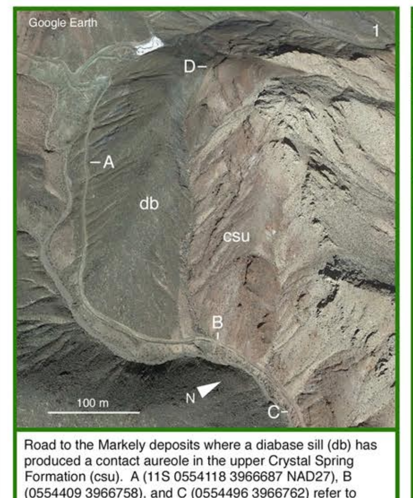


Chilled diabase contact exposed on wall of Timmy deposit workings. Beds are folded along contact, and diabase is stratigraphically above it. Location B on map. UTM location is 11S 0509898 3984440 NAD27.

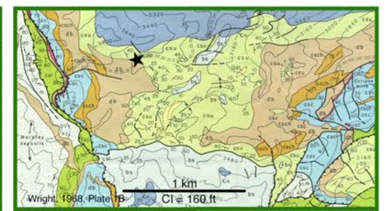
Stratigraphy of diabase sills in the Crystal Spring Formation



Markley road, central Ibex Hills



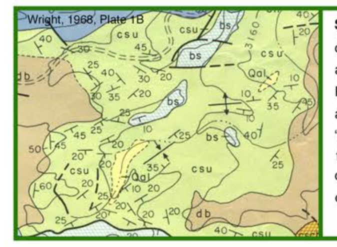
Road to the Markely deposits where a diabase sill (db) has produced a contact aureole in the upper Crystal Spring Formation (csu). A (11S 0554118 3966687 NAD27), B (0554409 3966758), and C (0554496 3966762) refer to image locations along the road or in the adjacent wash. From B to D the upper contact of the sill ramps up through the csu section. From B to C the upper part of the sill is well exposed on the north side of the wash below the elevation of the road (see image 2). This latter detail is not shown on the Markley road map.



Road to Markley deposits, central Ibex Hills

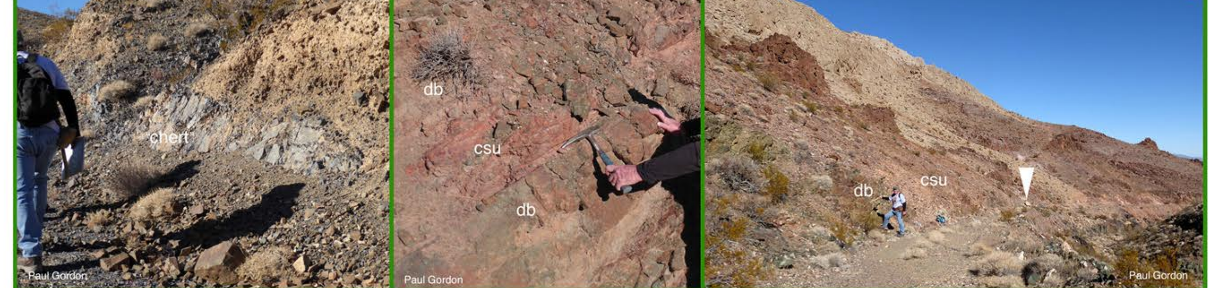
- Єn Noonday Dolomite
- bs Beck Spring Dolomite
- db Crystal Spring Diabase
- csu Upper Crystal Spring Formation (a.k.a. Horse Thief Spring Formation)
- csch Massive chert of csc
- csc Middle Crystal Spring Formation
- csl Lower Crystal Spring Formation
- sc Silicated rock including talc
- ★ is at 11S 0554409 3966758 NAD27 (B on image 1)

View downstream to the east from location C. The upper contact of the sill is approximately coincident with the top of the exposed diabase (db).



Syn-intrusive structures: Sears proposes that differential inflation of diabase sills caused folding and faulting of the overlying upper Crystal Spring Formation in the Saratoga Hills, Alexander Hills, and eastern Kingston Range. This detail from the "Road to the Markley deposits" map shows folding and numerous changes in attitude in the csu overlying the diabase sill, a possible example of syn-intrusive structures.

Diabase sill and its contact aureole in the upper Crystal Spring Fm from A to C on image 1



Chert member of the middle Crystal Spring Fm at the base of this diabase sill at 11S 0554118 3966687 NAD27 (A in image 1).

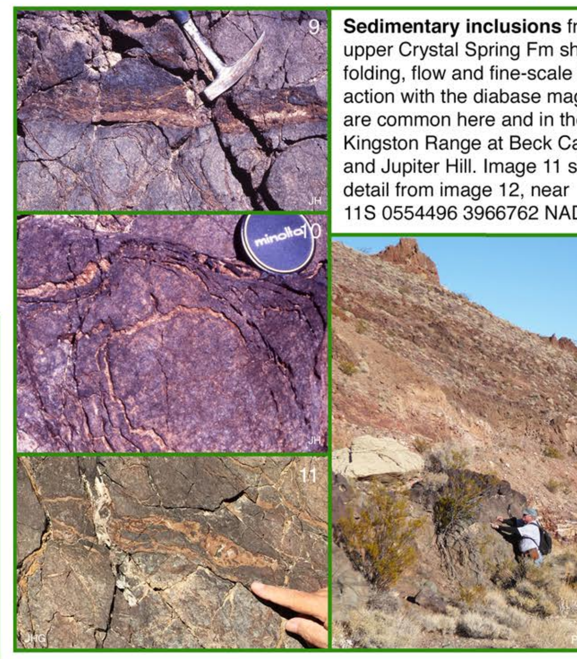
Upper Crystal Spring Fm units inter-fingering with diabase at 11S 0554152 396654 NAD27 near A.

Diabase and overlying aureole at 11S 0554409 3966758 (B on image 1). Arrow marks boulder in images 6 and 7.

Contact aureole in upper Crystal Spring Fm between B and C on image 1

Continuation of image 6, note large tan boulder in both 6 and 7.

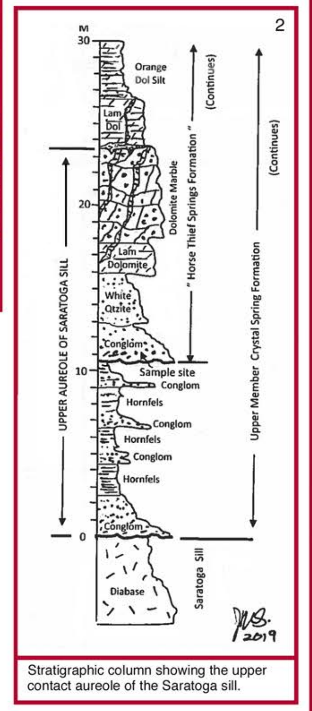
Contact metamorphic aureole near C in image 1, 11S 0554496 3966762.



Sedimentary inclusions from the upper Crystal Spring Fm showing folding, flow and fine-scale inter-action with the diabase magma are common here and in the Kingston Range at Beck Canyon and Jupiter Hill. Image 11 shows detail from image 12, near 11S 0554496 3966762 NAD27

Saratoga Spring, southern Ibex Hills

View to east in the Saratoga Spring parking lot. The east-dipping Saratoga sill, dated at 1.067 Ga (Heaman and Grotzinger, 1992), lies between the dolomite of the middle Crystal Spring Fm and the Horse Thief Spring Fm (formerly upper Crystal Spring Fm). From 11S 0552583 3948453 NAD27.



Stratigraphic column showing the upper contact aureole of the Saratoga sill.

Based on samples from Saratoga Spring, Mahon et al (2014) claim that the depositional age for the conglomerate in images 5 and 9 is <787 Ma, and that the channeled erosional surface on which the conglomerate rests is a major regional unconformity. Here is evidence that these strata were deposited before the 1.1 Ga Crystal Spring diabase intruded.

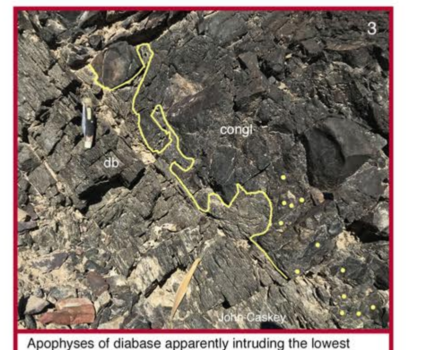
The Saratoga sill of the Crystal Spring diabase is green-black due to chloritic alteration and is laced with epidote and quartz veins (image 1). This and the significant hydrothermal alteration near its contacts suggests the sill was hydrated by fluids drawn from the host strata.

Sears mapped the Saratoga Hills and measured the section containing the site with anomalously young detrital zircons. He reports that at this Saratoga Spring section, the conglomerate chosen as the base of the Horse Thief Spring Fm is but the uppermost of 5 similar conglomerates, as shown on the stratigraphic column (image 2). The lowermost of these conglomerates is in intrusive contact with the Saratoga diabase sill (images 3 and 4)

The 5 conglomerates are similar in composition with platy hornfelsic clasts up to 9 cm wide and 2 cm thick and sub-rounded quartz pebbles in a quartzose matrix in the thicker units (image 5). The intermediate thinner conglomerates having a smaller clast size. Dark hornfelsic argillite layers separate the conglomerates (images 2 and 9). The darkening is attributed to the reaction with contact metamorphic fluids rising from the diabase. The conglomerates are similarly darkened with black iron oxide in the matrix. Darkening is greatest adjacent to the diabase with black overgrowths on the quartz grains making the conglomeratic character indistinct. Upward through the section, with decreasing metamorphic grade, the quartz grains are seen as well rounded, coarse white sand (images 6 and 7).

The uppermost conglomerate is overlain by a 3-m thick white recrystallized quartzite followed by a 9-m section of dolomite (image 2). At the Saratoga Spring section, the main mass of dolomite is a coarsely crystalline marble with euhedral crystals as large as 5 mm. Crystal-lined vugs about 1 cm in diameter are abundant, and vertical pipes displaying varying crystal sizes played a role in the marbleization. The overlying dolomitic silt evidently served as a barrier to rising metamorphic fluids.

Because the Saratoga sill ramps up through the section from the north to the south, these conglomerates and dolomite are not metamorphosed to the north at the measured reference section of Mahon et al (2014). There the sampled conglomerate layer is more than40 m above the diabase (per Mahon, et al, 2014, Table DR2) instead of 11 m above it is at the Saratoga Spring section.



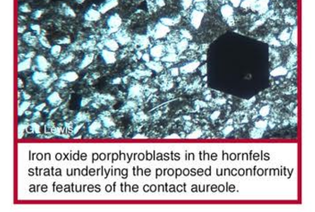
Apophyses of diabase apparently intruding the lowest conglomerate in image 2. The black color, due to hornfelsic contact metamorphism, obscures the pebbles. Selected pebble locations are shown by dots. Clasts are similar to those of the dated conglomerate (see image 5).

Location of image 3 seen from the road. See image 8 also.

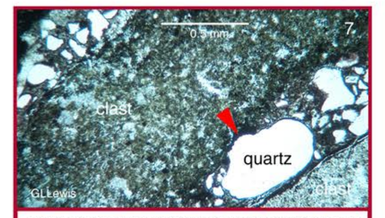
Conglomerate with hornfels and quartz clasts which yielded the 6 detrital zircons having Neo-proterozoic ages reported by Mahon et al, 2014.

Non-polarized scan of a thin section of the conglomerate in image 5. Note the iron oxide blebs in the matrix and pervasive chloritic alteration.

View along strike of section shown in the stratigraphic column (image 2). A is the diabase at the base of the column, and B is the lowermost conglomerate (both shown in image 3). C is alternating hornfels and three thin conglomerate layers. D is the uppermost conglomerate (image 5). E is dolomite marble.

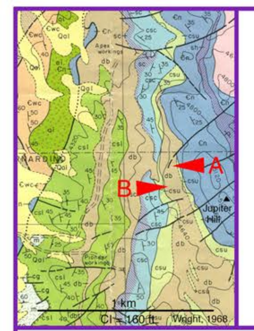


Iron oxide porphyroblasts in the hornfels strata underlying the proposed unconformity are features of the contact aureole.



Plane-polarized view of the area in the red rectangle in image 6 showing post-depositional iron oxide rimming a quartz grain (at arrow) and chlorite developed in both the clasts and the matrix.

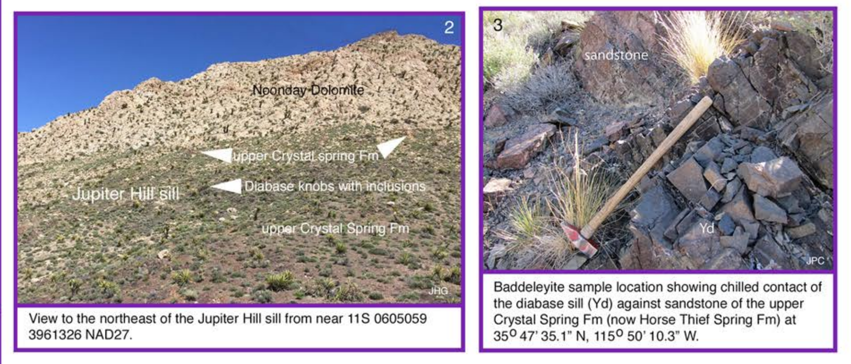
Jupiter Hill area, eastern Kingston Range



Jupiter Hill area, eastern Kingston Range

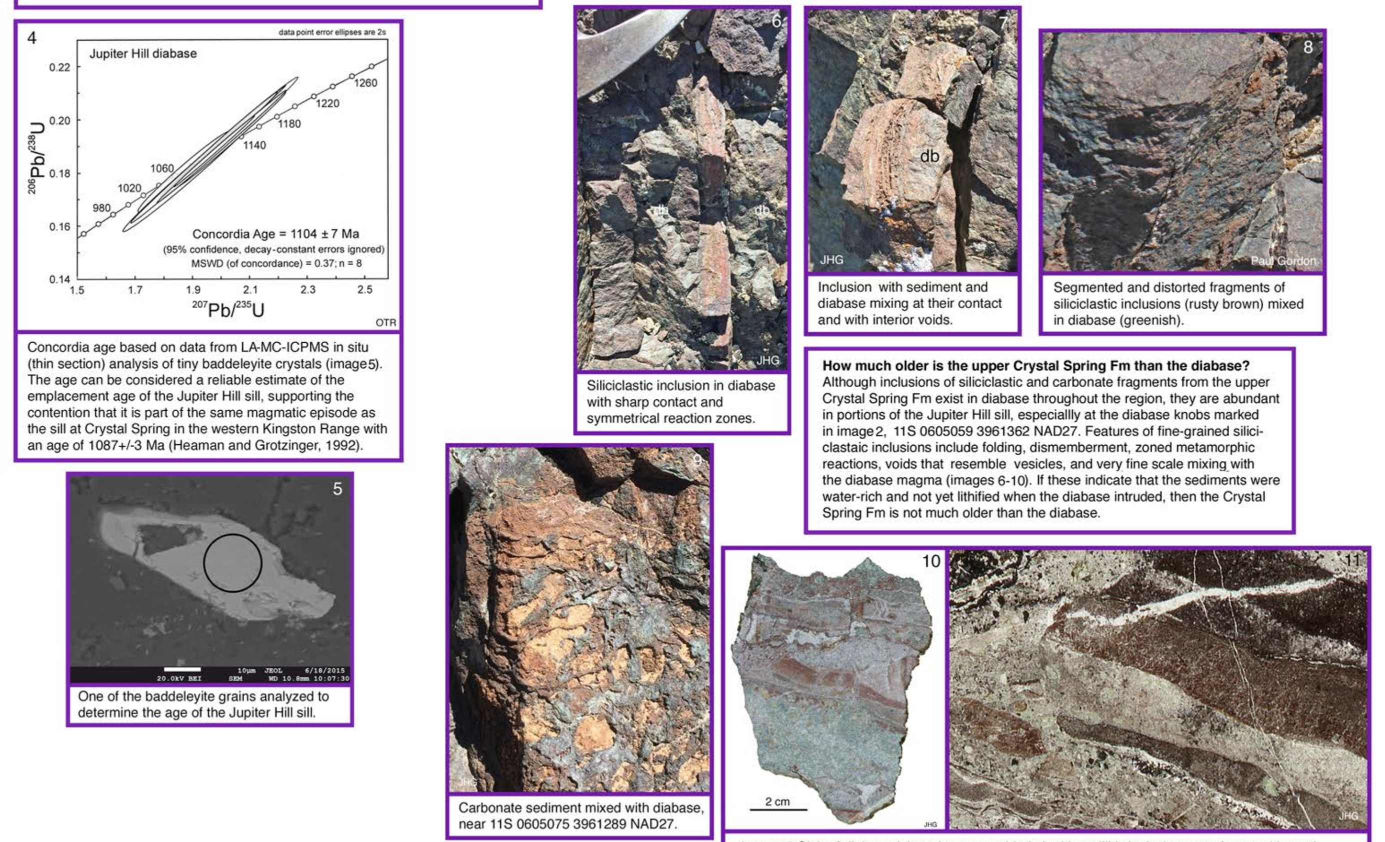
- Noonday Dolomite
- Crystal Spring Diabase
- Upper Crystal Spring Formation (a.k.a. Horse Thief Spring Formation)
- Middle Crystal Spring Formation
- Lower Crystal Spring Formation
- Silicated rock including talc
- A is location of the dated diabase sample.
- B is area of inclusions in images 6-10.

The Jupiter Hill diabase sill is the stratigraphically highest of the intrusions in the eastern Kingston Range. It intrudes the upper Crystal Spring Fm (now Horse Thief Spring Fm), and its baddeleyite age of 1104+/- 7 Ma is important in establishing that the Horse Thief Spring Fm cannot be as young as 787 Ma.



View to the northeast of the Jupiter Hill sill from near 11S 0605059 3961326 NAD27.

Baddeleyite sample location showing chilled contact of the diabase sill (Yd) against sandstone of the upper Crystal Spring Fm (now Horse Thief Spring Fm) at 35°47' 35.1" N, 115° 50' 10.3" W.



Concordia age based on data from LA-MC-ICPMS in situ (thin section) analysis of tiny baddeleyite crystals (image5). The age can be considered a reliable estimate of the emplacement age of the Jupiter Hill sill, supporting the contention that it is part of the same magmatic episode as the sill at Crystal Spring in the western Kingston Range with an age of 1087+/-3 Ma (Heaman and Grotzinger, 1992).

One of the baddeleyite grains analyzed to determine the age of the Jupiter Hill sill.

Siliciclastic inclusion in diabase with sharp contact and symmetrical reaction zones.

Inclusion with sediment and diabase mixing at their contact and with interior voids.

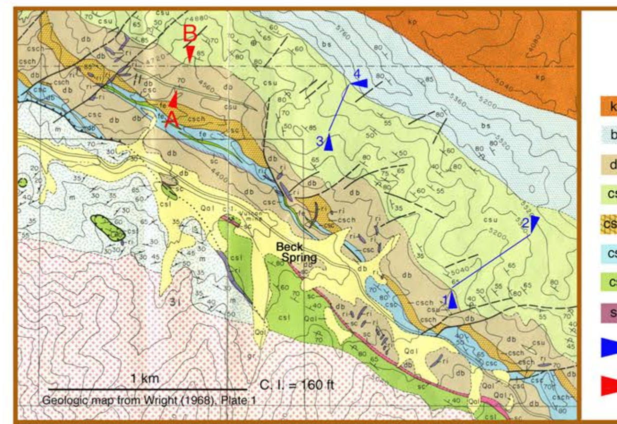
Segmented and distorted fragments of siliciclastic inclusions (rusty brown) mixed in diabase (greenish).

How much older is the upper Crystal Spring Fm than the diabase? Although inclusions of siliciclastic and carbonate fragments from the upper Crystal Spring Fm exist in diabase throughout the region, they are abundant in portions of the Jupiter Hill sill, especially at the diabase knobs marked in image 2. 11S 0605069 3961262 NAD27. Features of fine-grained siliciclastic inclusions include folding, dismemberment, zoned metamorphic reactions, voids that resemble vesicles, and very fine scale mixing with the diabase magma (images 6-10). If these indicate that the sediments were water-rich and not yet lithified when the diabase intruded, then the Crystal Spring Fm is not much older than the diabase.

Carbonate sediment mixed with diabase, near 11S 0605075 3961289 NAD27.

Image10:Slab of diabase (altered to green chlorite) with argillitic inclusion parts (rust and brown) shown in cross section is a good example of the fine scale interaction between the sediment and the magma. The irregular white field is secondary quartz. Image 11 is an enlargement of a thin section (non-polarized light, field of view 2 cm across) cut from the slab showing mobilization of iron oxides, reaction zones, and the growth of new crystals on the finest scales.

Beck Canyon, Kingston Range

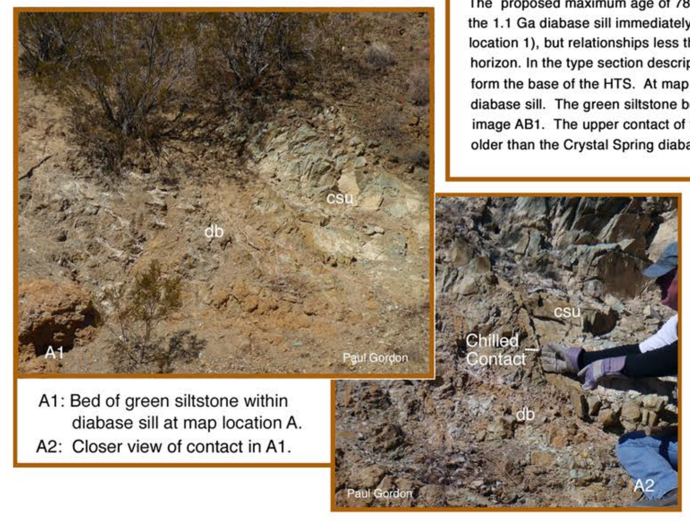


Beck Canyon
Kingston Range, CA

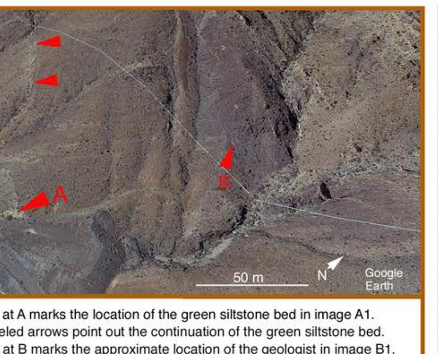
Pahrump Group

- kp Kingston Peak Formation
- bs Beck Spring Dolomite
- db Crystal Spring Diabase
- csu Upper Crystal Spring Formation (a.k.a. Horse Thief Spring Formation)
- csch Massive chert of csc
- csc Middle Crystal Spring Formation
- csl Lower Crystal Spring Formation
- sc Silicated rock including talc
- Horse Thief Spring Fm type section per Mahon et al (2014) GPS data
- Locations for this study
  - A 11S 0595870 3961243 NAD27
  - B 11S 0595938 3961398 NAD27

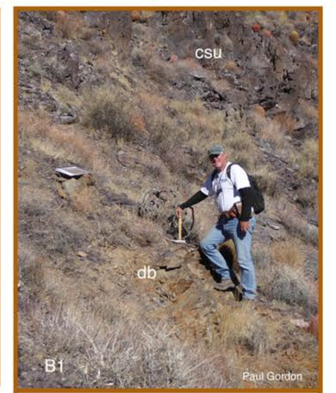
The proposed maximum age of 787 Ma for the Horse Thief Spring Formation (HTS) requires an unconformity at the contact with the 1.1 Ga diabase sill immediately below the type section (Mahon et al, 2014). This contact is covered at the type section (map location 1), but relationships less than 2 km to the NW (map locations A and B) preclude the existence of an unconformity at that horizon. In the type section description (Mahon et al, 2014,Table DR1), a green hornfelsic siltstone succeeded by purple siltstone form the base of the HTS. At map location A, a bed of green siltstone (shown in images AB1, A1, and A2) resides within the diabase sill. The green siltstone bed is continuous enough to have been previously mapped (csu at A) and to be obvious on image AB1. The upper contact of the sill is overlain by purple siltstone (image B1). These relationships require the HTS to be older than the Crystal Spring diabase.



A1: Bed of green siltstone within diabase sill at map location A.
A2: Closer view of contact in A1.



Arrow at A marks the location of the green siltstone bed in image A1. Unlabeled arrows point out the continuation of the green siltstone bed. Arrow at B marks the approximate location of the geologist in image B1. (The pale thin line is the San Bernardino-Inyo County Line.)



Diabase sill overlain by purple siltstone at map location B.