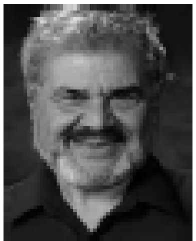
The Meteorites of California

By Derek Sears and Robert Verish

The meteorites of a region are a reflection both of its history and geography. They also trace the continually unfolding story of what these objects tell us about our solar system and of the personalities involved in their collection and study. This was never truer than it is for the meteorites of California.

California is a huge state with a huge population. Over 37 million people live in its 424,000 square kilometers. There is a variety of geographical regions, from the rolling coastal range on the west, to the Sierra Nevada Mountains on the east, the deserts of the south and the heavily forested Cascade Mountains of the north. Down the middle, like the gouge of some giant sculptor's thumb, is the highly fertile central valley. The state boasts both the highest and the lowest elevations in the continental U.S., Mount Whitney at 4,400 m and Death Valley 884 m below sea level. It comes as no surprise therefore that the number of meteorites being recorded in this state is large and that they are not uniformly found over the state.

The largest of the California meteorites are the famous Old Woman meteorite at 2.27 metric tons and the Goose Lake meteorite at 1.17 metric tons. The smallest is a one half gram chip of an H6 chondrite found on Cuddeback Dry Lake in the southern deserts in 2000. The large meteorites tend to be recovered in the forests or the mountains, where deer hunters or gold hunters stumble across them. The vast majority of California finds come from the southern deserts, where they are found in spectacular numbers exposed on the surface of dry lake beds, or playas. Only three have been found in the fertile Central Valley and Imperial Valley, despite intensive farming, and these were only encountered at depth in the ground by farmers while they were digging fence-post holes.

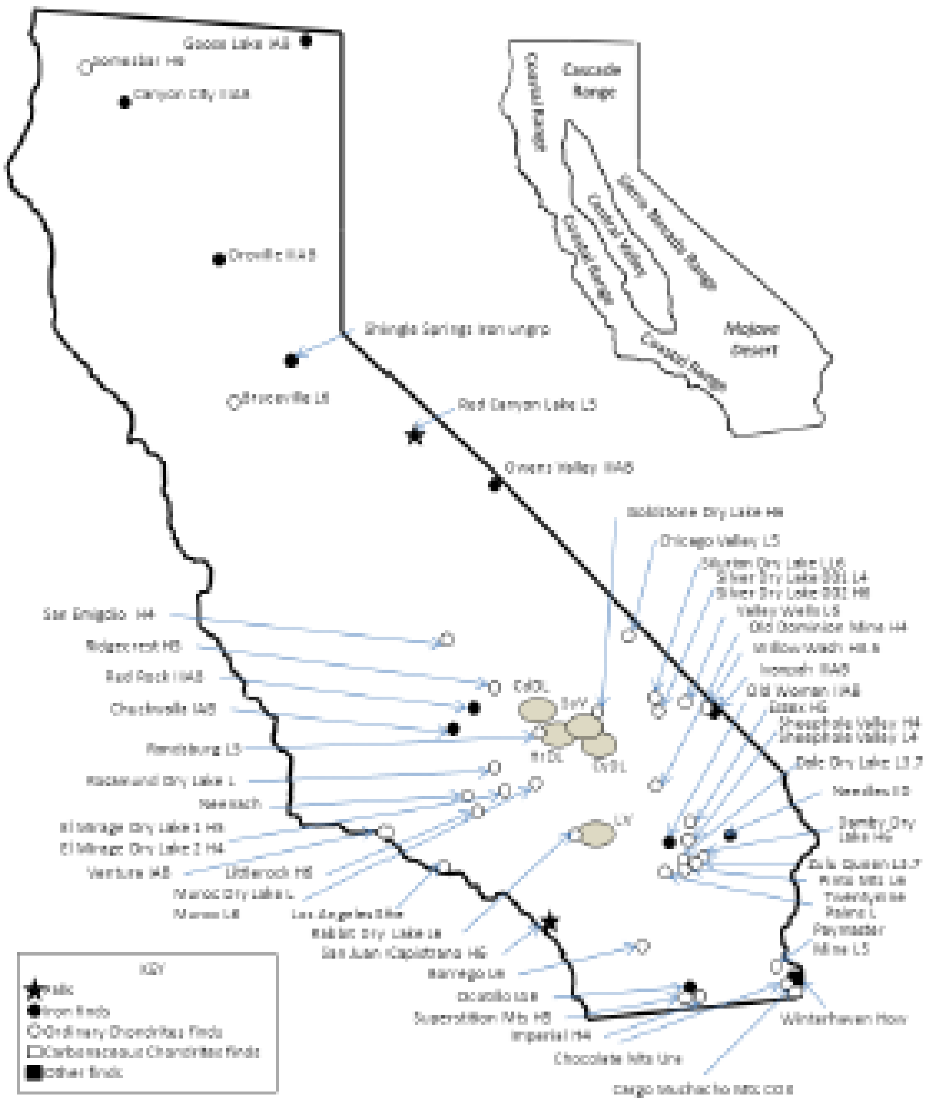
Thirteen of the meteorites are irons, which tend to be large and predominate among the meteorites found early on California's history. These are alloys of iron and nickel, with amounts of minor and trace elements, thought to be from the cores of their parent asteroids, or occasionally from large pools of metal on the asteroid. Most of the meteorites are varieties of chondrite, this class having compositions similar to the Sun's photosphere in all but the most volatile elements, although subtle variations in composition have led to the definition of many subclasses like carbonaceous

Table 1. Meteorites of California*†

Meteorite	Year	Class	Mass (g)	Meteorite	Year	Class	Mass (g)
Irons				**Chondrites (continued)**			
Shingle Springs	1869	Iron ungr	39,000	Zulu Queen	1976	L3.7	200
Canyon City	1875	IIIAB	8,600	Littlerock	1979	H6	19,000
Ivanpah	1880	IIIAB	58,000	Somersbar	1997	H6	60
Oroville	1893	IIIAB	24,500	Bruceville	1998	L6	85,000
Surprise Springs	1899	IAB-sLL	1500	Goldstone DL	1998	H6	1.1
Owens Valley	1913	IIIAB	192,800	Sheephole Valley	1998	H4	62.1
Goose Lake	1938	IAB-sLL	2,340,000	Sheephole Valley 2	1998	L4	4.4
Yermo	1955	IAB-ung	7,700	Cargo Muchacho Mts	2000	CO3	2,880
Needles	1962	IID	45,500	Danby Dry Lake	2000	H6	8,990
Old Woman	1976	IIAB	5,500,000	El Mirage DL 001	2000	H5	1.5
Red Rock	1976	IIIAB	47,000	Old Dominion Mine	2000	H4	42
Ocotillo	1990	IAB-MG	8,570	Rabbit Dry Lake	2000	L6	20
Chuckwalla	1992	IAB-MG	1802	Silurian Dry Lake	2000	LL6	43.8
Chondrites				Silver Dry Lake 001	2000	L4	219
San Emigdio	1887	H4	36,000	Silver Dry Lake 002	2000	H6	16.5
Imperial	1908	H4	4	Superstition Mts	2000	H5	222
Valley Wells	1929	L6	129.9	El Mirage DL 002	2001	H4	13
Borrego	1930	L6	2,130	Chicago Valley	2004	L5	26
Muroc	1936	L6	18.4	Paymaster Mine	2004	L5	159
Muroc Dry Lake	1936	L6	223	Randsburg	2005	L5	112.9
Rosamond Dry Lake	1940	L6	850	Willow Wash	2006	H3.5	552
Twentynine Palms	1944	L6	100	Red Canyon Lake	2007	H5	18.4
Neenach	1948	L6	13,800	**Non-chondrites**			
Pinto Mountains	1954	L6	37,000	Los Angeles	1999	Shergottite	698
Dale Dry Lake	1957	L3.7	200	SuV 014	2002	Acapulcoite	1.77
Ridgecrest	1958	H5	5.7	Winterhaven	2002 / 2003	Howardite	2,100
San Juan Capistrano	1973	H6	56	Chocolate Mts	2004	Ureilite	659

* Excluding the meteorites found on Lucerne Valley, Coyote Dry Lake, Harper Dry Lake, Cuddeback Dry Lake, Superior Valley (see separate table)

† As of June 2011.



Map showing the locations of all the California meteorites as of summer 2011 with an inset indicating the geographical regions.

Table 2. The Meteorites of California collected from the major dry lakes*

	Lucerne Valley	Coyote Dry Lake	Harper Dry Lake	Cuddeback Dry Lake	Superior Valley
Abbreviation	LV	CyDL	HrDL	CdDL	SuV
Number of finds	121	218	26	30	31
Classified finds	82	52	12	20	17
Years	1963-2010	1995-2008	1999-2010	1999-2008	2000-2006
Total mass (g)	630	16,804	880	695	1000
No meteorites with mass >1 kg	0	5	0	0	0
Total mass (g) without >1 kg	630	4,291	880	695	1000
Ave mass (g) without >1 kg	10.9	82.5	31.4	23.9	58.9
Notes	Fourteen CK4-5, others EOC	All EOC One H3	Two UOC(HrDL 001, 004), 16 unknown, others EOC	Nine unknown, others EOC	One acapulcoite (SuV 014), others EOC

* As of June 2011.

Shingle Springs meteorite from Silliman's 1873 article.

Canyon City meteorite from Ward's 1905 article.

chondrites (represented among the California meteorites by the CK and CO chondrites), ordinary chondrites (H, L, and LL classes), and enstatite chondrites (absent in the Californian meteorites). Finally, there are four stony meteorites in the Californian collections that are either igneous rocks, produced by some form of volcanism, or chondrites that are so altered by heat or mixing that they are recognized as an entirely different type of meteorite.

The irons

The first meteorite to be found in California was an iron meteorite found in 1869 at Shingle Springs, El Dorado County, and a few years later described independently by Benjamin Silliman Jr. (professor at Yale University known for his association with the early oil industry) and Charles Upton Shepard (curator of meteorites at the Smithsonian Institution). Much to the scientists' dismay, the mass showed no internal structure using then normal mid nineteenth century method of heavily etching and then using the meteorite as a printing block. To this day the first California meteorite remains "ungrouped", although texturally it is referred to as an "ataxite".

Six years later another iron meteorite was found but this time it was hidden from science for 25 years being wrapped in a napkin and shown only to the friends of its finder. Eventually reports reached Shepard and H. A. Ward who obtained chips for analysis. They named the meteorite Canyon City and produced an image of the meteorite showing the Widmanstätten structure.

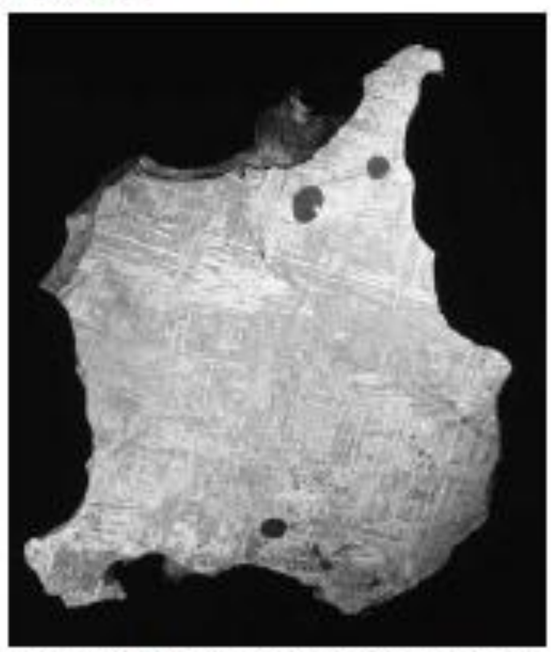
Three more large iron meteorites were to be recovered during the late nineteenth century. Ivanpah was found in a wash in the mountains by a prospector because of the ring it made under his hammer. The meteorite was given to the state geologist who sent chips to Charles Upton who described it in the American Journal of Science. Oroville appears not to have been described in the technical literature but was included in a catalog of meteorites published by Oliver Cummings Farrington of the Field Museum in Chicago in 1915. Surprise Springs, a 1.4 kg iron meteorite found in 1899, was described by another well-known early twentieth century worker on meteorites, E. Cohen after whom the phosphide mineral cohenite was named. His description appeared in the German journal Naturwissenschaften and the meteorite was listed in Farrington's 1915 catalog. The first twentieth century Californian iron meteorite was found just before the first world-war and is now preserved in the Smithsonian Institution. The 193 kg Owens Valley meteorite was described in 1922 by another important figure in meteorite studies, G. P. Merrill, the then curator for meteorites at the Smithsonian. The Californian iron meteorites are associated with some of the most important scientists in the history of meteorite studies.

The massive Goose Lake meteorite (1.17 metric ton) was found by three deer hunters who took chips to scientists at the Griffith Observatory for identification. When it was realized that it was a meteorite a team including Harvey Nininger and Fredrick Leonard, also important characters in the history of meteorite studies and both founding members of the Meteoritical Society, set out to recover the meteorite. It was realized that the meteorite was on federal land and belonged to the U.S. government so after being displayed at the Golden Gate International Exposition during 1939/40 was placed in the Smithsonian Institution collections. Nininger described the events in his catalog "The Nininger Collection of Meteorites" but evidently Leonard thought he exaggerated his role. Leonard wrote an article in which he said:

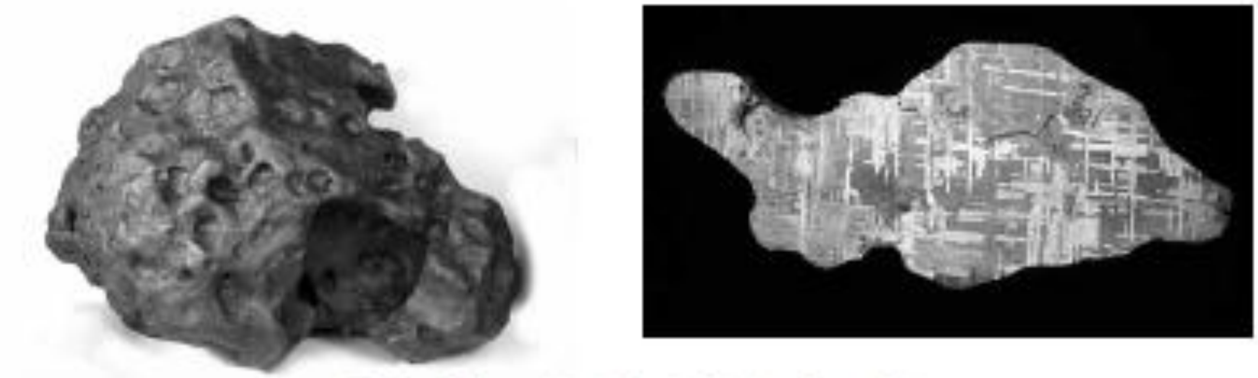
> *In due justice to all concerned, the credit for the recovery of the Goose Lake meteorite should go to and should be shared equally by Earl G. Lindsley, Addie D. and H. H. Nininger, and me.*

Richard Norton discussed the history of this meteorite in the November 1999 issue of *Meteorite*.

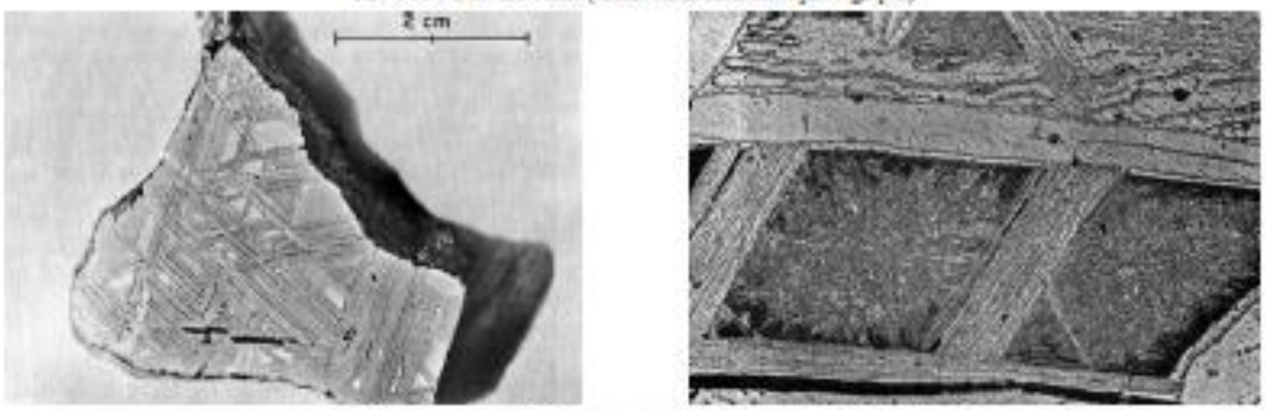
It was another forty-four years until the next iron meteorite was recovered in California. In 1962 amateur rock hunters found a 45.3 kg iron meteorite in the Turtle Mountains south of Needles. Five years later UCLA professor, John Wasson, succeeded in obtaining the meteorite for the Leonard meteorite collection at UCLA. This success led Wasson to organize annual trips to the desert for his students and research colleagues, including one of the present authors, to hunt for more meteorites.



The Owens Valley meteorite (Smithsonian Institution photo)



The Goose Lake meteorite (Smithsonian Institution photographs)



The Needles meteorite from a paper by Wasson and Kimberlin

Wasson was also involved in the recovery of the next Californian iron, the largest of the Californian meteorites, Old Woman. At 2.75 metric ton, this meteorite is the second largest U.S. meteorite, after Willamette meteorite that was found in Oregon. It is 38 inches (97 cm) long, 30 inches (76 cm) wide, and 34 inches (56 cm) high. The Old Woman meteorite was found by three prospectors who brought the Smithsonian's curator for meteorites, Roy Clarke, to the site to inspect the mass. Wasson and Clarke had very different ideas as to the final disposition of the iron, but the result was that the meteorite was cut so that a section could be preserved in Washington DC while the main mass could reside in a museum in Barstow.

The 47.6 kg Red Rock meteorite was recovered in the same year as Needles while the smaller Ocotillo and Chukwalla meteorites, the last of the Californian irons to be found, had to wait until the early nineties for their discovery.

With the exception of Shingle Springs, all of the Californian iron meteorites show the Widmanstätten structure of kamacite bands in an octahedral configuration embedded in taenite, kamacite being the low nickel iron-nickel alloy and taenite being the high nickel form of the iron-nickel alloy. From the width of the bands, fine (0.2-0.5 mm) for which t here is no Calkifornian representative, to medium (0.5-1.3 mm) for Red Rock, and coarsest >3.3 mm for Old Woman, and the central nickel content of the bands, it has been possible to estimate the rate at which the meteorites cooled during their formation and this enables burial depths to be determined. For example the cooling rates of chemical groups I, IIIAB and IVA are 400–4000°C/106years, 150–1400°C/ 106 years and 750–6000°C/106years, respectively.

All of the Californian iron meteorites have been analyzed, most notably for nickel, germanium, and gallium from which they have been assigned to classes, although Shingle Springs again refuses classification and remains ungrouped.

The chondrite finds

Only fourteen of the more than 180 chondrite classified finds have masses greater than 1 kg, and only six are greater than 10 kg. The first recovered and second largest of the Californian stony meteorites is the San Emigdio H4 chondrite that was found in 1887 by prospectors who, thinking it to be an ore, had crushed and destroyed the main mass. The information available is from chips sent for formal assay and passed on to G. P. Merrill who made sections and arranged for an analysis. The largest Californian chondrite is Bruceville, an 83 kg L6 stony meteorite currently at the Griffith Observatory in Los Angeles. The remaining three Californian chondrites larger than 10 kg are Neenach, an L6 chondrite found in 1948 (13.8 kg), Pinto Mountains, an L6 chondrite found in 1954 (37.6 kg) and Littlerock, an H6 chondrite found in 1979 (19.0 kg).

In 1955 the finder of the Pinto Mountains meteorite, Vincenze Zimmerman, made a subsequent recovery of a 19.7kg mass which was later sold to H. H. Nininger. Unfortunately this mass was named "Twentynine Palms" which was an oversight, since that same name had already been assigned to the 100g mass found by Morris Ojeda in 1944. This "oversight" has caused some confusion in the recorded history of these two "Twentynine Palms" masses. But a recent analysis by Dr. Alan Rubin (UCLA) has shown that, although both of these chondritic stones are now classified as L6, they are distinctly unpaired. In addition, the 19.7kg mass from 1955 was found to be paired to the Pinto Mountains L6 chondrite, effectively becoming the main-mass for that meteorite.

There are eight chondrites greater than 1 kg. Borrego is a 2.13 kg L6 chondrite about which is little is known. Four Coyote Dry Lake H5 chondrites CyDL 024 (2.43 kg), 033 (5.22 kg), 061 (2.13 kg), 064 (1.36 kg), are paired with CyDL 001, while the Coyote Dry Lake 115 H5-6 chondrite (1.37 kg) is paired to CyDL 002. The H6 Danby Dry Lake H6 chondrite (8.99 kg) is a monomict impact-melt breccia. Fibrally, the Essex H5 chondrite (5 kg) comes from a strewn field has yet to be found.

There are a few meteorites <1 kg that are especially interesting. Of the small and especially important ordinary chondrites are the Dale Dry Lake and Zulu Queen L3.7 meteorites that were found 15 km apart by the same finder and it has been suggested that they are "paired", that is fragments of the same original meteorite. Another is low petrographic type chondrite is Willow Wash, an H3.5 chondrite. The relatively low petrographic type reflects a meteorite that has suffered minor metamorphism, alteration by heating in their parent body, the internal texture of glassy chondrules, matrix and metal and sulfide grains are still easily seen under a low powered microscope.

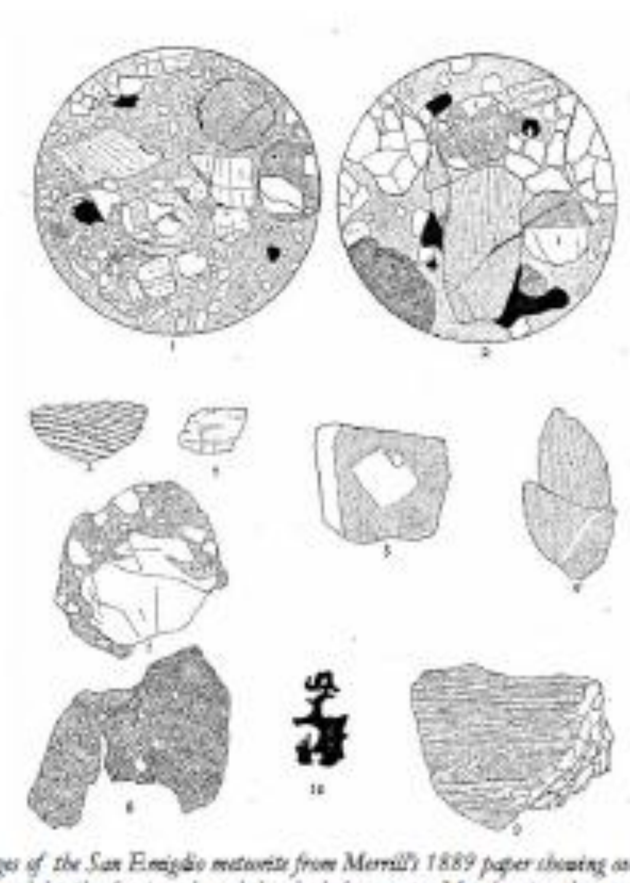
Among the Californian chondrite finds are two carbonaceous chondrites, one CO3 and one CK, in fact the CK chondrite consists of ten separate fragments that are assumed to be pieces of a single meteorite. Among the chondrites from California are two carbonaceous chondrites, one CO3 and one CK4-5, in fact the CO3 comprises a 32 member strewn field whose classifications have not yet appeared in the Meteoritical Bulletin and are not included in tables, The CK4 consists of numerous, small internal fragments (fourteen of which have been classified) that are assumed to be all from the same fall.

The CK chondrites are similar to the better known CV and CO chondrites but noted for their relatively high level of metamorphism (petrographic type 4-6). The CO chondrites are a group of carbonaceous chondrites having petrographic type 3 levels of metamorphism but slightly closer to solar compositions than the CV and CK chondrites.

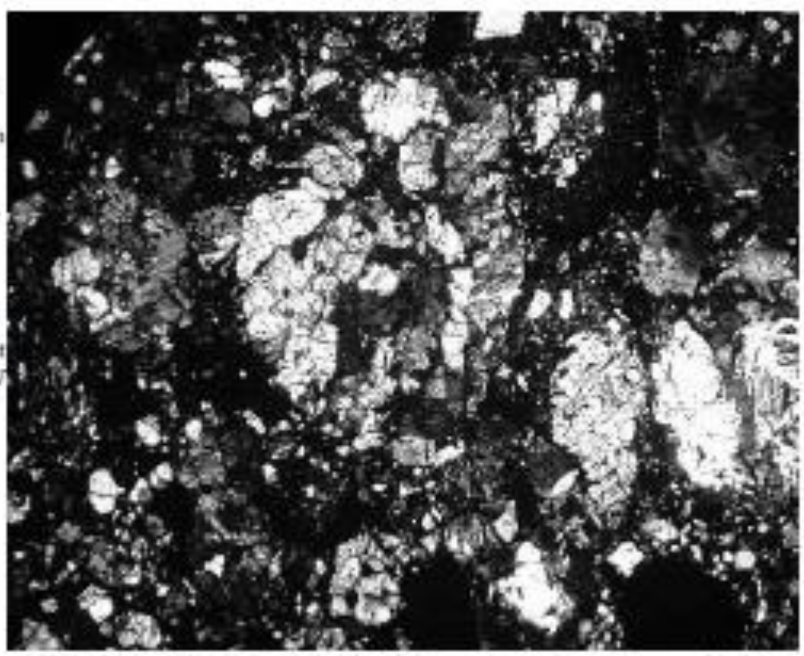
The non-chondrite finds

Of the remaining stony categories, there are only single examples of the rare classes, such as Acapulcoite (SuV 014), Howardite (Winterhaven), Shergottite (Los Angeles) and Ureilite (Chocolate Mountains).

Superior Valley 014 is a 1.77 g meteorite that was found in 2002 and is one of the primitive achondrites resembling the first meteorite of this type recognized, namely Acapulco. These meteorites are essentially



Images of the San Emigdio meteorite from Merrill's 1889 paper showing overall texture and details of minerals and chondrule fragments. Metal grains shown as black, radiating structures are enstatite, clear portions are olivine, while dotted areas are fine grained and oxide stained regions. The grains are ~0.5 mm in size.



Zulu Queen under an optical microscope showing sharpness of textures and large chondrules embedded in fine grained crystallized matrix (Photograph by Bob Verish) chondrites that have been heavily metamorphosed and even partially melted to the point that they no longer have the distinctive chondrite appearance under the microscope – chondrules surrounded by a matrix of chondrule and mineral fragments, sulfide and metal grains - and begin to look like achondrites.

The Los Angeles meteorite consists of two fragments, weighing 452.6 and 245.4 g, found by one of the authors (RV) in a collection of rocks collected in the Mojave Desert in the late 1970s or early 1980s and recognized in 1999 as a Shergottite. The shergottite meteorites, named after an Indian Shergotty meteorite, are basalts that are now known to have come from Mars. A distinctive feature of these meteorites is that unlike their terrestrial counterpart the abundant feldspar they contain has been converted into a strange and highly unstable glass that has retained the outline of the parent crystals. This phase is named maskelynite after a nineteenth century curator of meteorites at the British Museum.

One of the authors (Bob Verish) holding the two specimens of the Los Angeles martian meteorite (Photograph by Dave Andrews).

The 2.1 kg Winterhaven meteorite was found in 2002/3 and has the characteristics of a basalt-related breccia which is a rock mixture of Eucrites and Diogenites, related igneous meteorites related. These three meteorite types are commonly thought to have originated on the asteroid Vesta. Winterhaven was described in the technical literature by Joe Boesenberg of the American Museum of Natural History in New York.

The Chocolate Mountains 699 g meteorite that was found at the base of the Black Mountains in 2004 and is a member of the Ureilite class. Ureilites, named after the Novo-Urei, Russia, fall of 1886, are ultramafic (iron and magnesium rich) achondrites that contain interstitial carbon as graphite or diamond. About 10% of Ureilites are polymict breccias, meaning they are lithified mixtures of a few percent of feldspar-like material in addition to typical ureilitic componentscollections of the department, had not been subject to any significant damage or loss. Under the microscope, Chocolate Moutains has mafic grains that are aligned and consist of just under equal amounts of olivine and pyroxene. Metal and carbon-rich material exists between the grains, but much metal is weathered.

The Dry Lake Finds

It has long been known that certain places on Earth were favorable for the recovery of meteorites. The first California dry lake meteorite finds, Muroc and Muroc Dry Lake, were made accidentally by Lee Humiston in 1936 when he was stationed there at a guard post while in the military service. The recovery of meteorites was transformed in the 1960s and 1970s when meteorites started to be recovered from Antarctica and the hot deserts in extraordinary numbers. The first dry lake meteorite to be found during an "intentional" meteorite-recovery search effort was made by Ron Hartman along with colleagues R. A. Oriti (Griffith Observatory) and Roderick W. Leonard, another six stones were found that same year (1963). Over the next five years various finders would recover another five stones and through the diligence of R. Oriti, then curator of the Griffith Observatory meteorite collection, all five were acquired and placed on exhibit. All of these specimens were found on the surface of Lucerne Dry Lake, in the area of an ellipse whose major axis does not exceed about 2.4 km.

To date, 62 specimens (672g) have been classified. An additional 59 finds have been made and have been assigned provisional numbers in the Meteoritical Bulletin Database. As mentioned above, fourteen fragments were classified as CK4-5 chondrites while the remainder are equilibrated ordinary chondrites (H, L, and LL chondrites of types 4 to 6).

There were no finds reported from other dry lakes until 1995 and the first decade of the twenty-first century when activity exploded. Next, Coyote Dry Lake was found to be a major source of meteorites by hunters like Robert Verish, Nicholas Gessler, Rob Matson, and Greg Stanley and to this point 318 meteorites have been recovered (with 52 finds being classified). There are five H5 and H6 chondrites with masses greater than 1 kg (CyDL 033, 5.22 kg, CyDL 024, 2.43 kg, CyDL 061, 2.13 kg, CyDL 115, 1,37 kg, CyDL 064, 1.36 kg). The remaining 47 classified CyDL meteorites total 82.5 g and are also all equilibrated ordinary chondrites, with the lone exception of CyDL 117 (H3) 162 g.

Harper Dry Lake (HrDL) has been searched by Bob Verish and colleagues

A selection of stones recovered by Peter and Jason Utas from Superior Dry Lake, including the Superior Valley 014 Acapulcoite. (Image by R. Verish) who to date have located 36 meteorites with a total mass of 880 g. Many of these meteorites have not yet been classified but among those that have are 16 equilibrated ordinary chondrites and two unequilibrated ordinary chondrites, HrDL 001 and HrDL 004 which are both LL4 chondrites.

Cuddeback Dry Lake (CdDL) has yielded 30 meteorites with a total mass of 693 g with Bob Verish playing the leading role in recovering meteorites from this location. To date 20 have been classified and they are all equilibrated ordinary chondrites.

Superior Valley (SuV) has produced 31 meteorites (17 classified finds) with a total mass of 1000 g with Robert Matson having greatest success at this site. Included in the meteorites from this site is the SuV 014 Acapulcoite discussed above (found by Jason Utas), while the others are all equilibrated ordinary chondrites.

The question arises of how such large numbers of meteorites came to exist on the dry lake beds. Ease of recognition is clearly the main factor and helps explain the large number of small meteorites that would not be easily visible on most other surfaces. Nevertheless, such large numbers beg for a more comprehensive explanation.

Mapping of find locations on a dry lake using GPS shows that there is a non-uniform distribution, or clustering, of these meteorites. These clusters have a high-ratio of unpaired meteorites, so the term "accumulation area" or "area of dense accumulation" better describes the fields. Because most dry lakes are known to be intermittently covered with standing water, a more descriptive term might be "stranding surface". Whatever term is used, they all hint that a concentration mechanism must exist.

In 2002 Gessler, Matson, and Verish have showed evidence for water-driven movement of rocks and meteorites on dry lakes, either by wave-action or ice and they suggested that this process causes their accumulation on these stranding surfaces. In the intervening years since 2002, much more evidence for movement of meteorites by wind-driven wave-action has been observed, which shows that this is not a random or rare occurrence. But regardless of how this concentration mechanism occurs, this process only applies to that area within a basin bounded by the margin of a standing body of water, or in other words, bordered by a shoreline. When one of us (RV) implores meteorite-hunters to "follow the ice-rafts" in order to find these stranding surfaces, we are limiting the success of recovery to only those meteorites which fell directly upon the dry lake. The assumption is that there is no other mechanism for influx of meteorites onto dry lakes.

This assumption has not always been widely accepted. In fact, prior to 2002 the conversation among fellow field workers (meteorite-hunters) showed that the majority felt that all these meteorites must be getting washed down the alluvial fans and out onto the dry lakes. But for the geologists who were trained in the principles of sedimentology, this was never a discussion. For instance, the process which produced the rock-free portions of a basin and, in turn, made the recognition of meteorites easier, that same process precludes that meteorites cannot be "washed-out onto a dry lake". As a researcher once remarked, "You can't have it both ways!"

So now, field-workers and researchers alike are unanimous that the best explanation for the large number of meteorites on dry lakes is ease of recognition. The main emphasis concern to field-workers and researchers is reconciling the rate of influx of meteorites on dry lakes with other well-documented areas such as Antarctica, Atacama Desert and Roosevelt County, New Mexico.

The Observed Falls

For a state the size of California, with its high population, it seems remarkable that only two meteorites have been observed to fall, and both are very small objects. The San Juan Capistrano meteorite was seen to fall on March 15, 1973, between midnight and 4:00 am local time. A 50.5 g fragment penetrated the aluminum sheeting roof of a carport in a mobile-home park and was picked up on the carport floor several hours later. A second fragment weighing 5.5 g was discovered about one month after the fall in the gutter of the carport roof. It was found to be an H6 chondrite. Studies of its cosmic ray history have shown that as with many meteorites of this class the meteorite is 4.5 billion years old and has been exposed to cosmic rays, and that is has been a meter-sized fragment for about 25 million years.

The Red Canyon Lake meteorite fell just after midnight on August 11, 2007 and a bright fireball moving in a S57°E direction was seen throughout northern and central California. There were many reports of sonic booms and ground shaking and the fireball was video recorded from Yuba City. A single black fusion-crusted stone weighing 18.4 g was picked up by a hiker near Red Canyon Lake. The meteorite was found to be an H5 chondrite.

Concluding remarks

It is very true that the nature of the recovery of California meteorites reflects its history and geography. The meteorites are fascinating, but viewing them through the lens of the state's geography and history adds a particular interest that we hope we have shared. The number of meteorites recovered in California makes it difficult to discuss every one in detail, but those discussed above give a feeling for the breadth of material that has been recovered from the state. The situation is very different from the 15 meteorites from Arkansas where the meteorites, discussed in the February 2011 issue of Meteorite, are few but all well-known and well-preserved. Many California meteorites are in the national museum in Washington D.C., essentially those recovered on federal land. Many have been kept in the state and are now on permanent display in recognized museums or observatories, but some are now lost and are known only because small chips were sent for analysis. Many are in private hands, especially the large number of recent finds in the dry lake beds. Some critically important meteorites have been found in the state, like the Los Angeles Martian meteorite.

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