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The Old Woman, California, IIAB iron meteorite

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Abstract–The Old Woman meteorite, discovered in March 1976 by two prospectors searching for a fabled lost Spanish gold mine in mountains ~270 km east of Los Angeles, has achieved the status of a legend among meteorite hunters and collectors. The question of the ownership of the 2753 kg group IIAB meteorite, the second largest ever found in the United States (34°28′N, 115°14′W), gave rise to disputes involving the finders, the Bureau of Land Management, the Secretary of the Department of the Interior, the State of California, the California members of the U.S. Congress, various museums in California, the Smithsonian Institution, and the Department of Justice. Ultimately, ownership of the meteorite was transferred to the Smithsonian under the powers of the 1906 Antiquities Act, a ruling upheld in a U.S. District Court and a U.S. Court of Appeals. After additional debate, the Smithsonian removed a large cut for study and curation, and for disbursement of specimens to qualified researchers. The main mass was then returned to California on long-term loan to the Bureau of Land Management's Desert Discovery Center in Barstow. The Old Woman meteorite litigation served as an important test case for the ownership and control of meteorites found on federal lands. The Old Woman meteorite appears to be structurally unique in containing both hexahedral and coarsest octahedral structures in the same mass, unique oriented schreibersites within hexahedral areas, and polycrystalline parent austenite crystals. These structures suggest that different portions of the meteorite may have transformed via different mechanisms upon subsolidus cooling, making the large slices of Old Woman promising targets for future research.

DISCOVERY OF THE METEORITE

The Old Woman meteorite was found in March 1976 by two prospectors, Mike Jendruczak and David Friburg, high up the wash of a canyon in the Old Woman Mountains in the Mojave Desert, some 270 km east of Los Angeles, while searching for a lost Spanish Conquistador gold mine rumored to be there (Fig. 1). As they struggled up one of the steep canyons on the mountainside, Jendruczak spotted a large 0.8 by 0.9 by 1.0 m dark-colored rock which stood out noticeably from all the light tan- and gray-colored boulders (Fig. 2). As he later recalled (Alexander 1977): "I tapped it, and right away I knew what it was. I'd seen pictures of meteorites in school and I've seen them in museums. So I was pretty sure it was a meteorite."

Over the next few months, the two prospectors and their partner Jack Harwood (who was not present the day the meteorite was found) tried to figure out what to do with their "Lucky Nugget" find. They thought about selling the meteorite to a university or museum, but first it would have to be moved from the mountains. They contemplated hiring a commercial helicopter to do this, and making a documentary film of the experience which they could then sell to television networks. But they lacked the funds needed to hire a helicopter.

To ensure that their find was indeed a meteorite, they removed a few small chips, and sent one to the Griffith Observatory in Los Angeles for verification. It was examined there by Ronald Oriti, the curator of the observatory's meteorite collection, who tested it for nickel. For reasons which are unclear, he did not detect

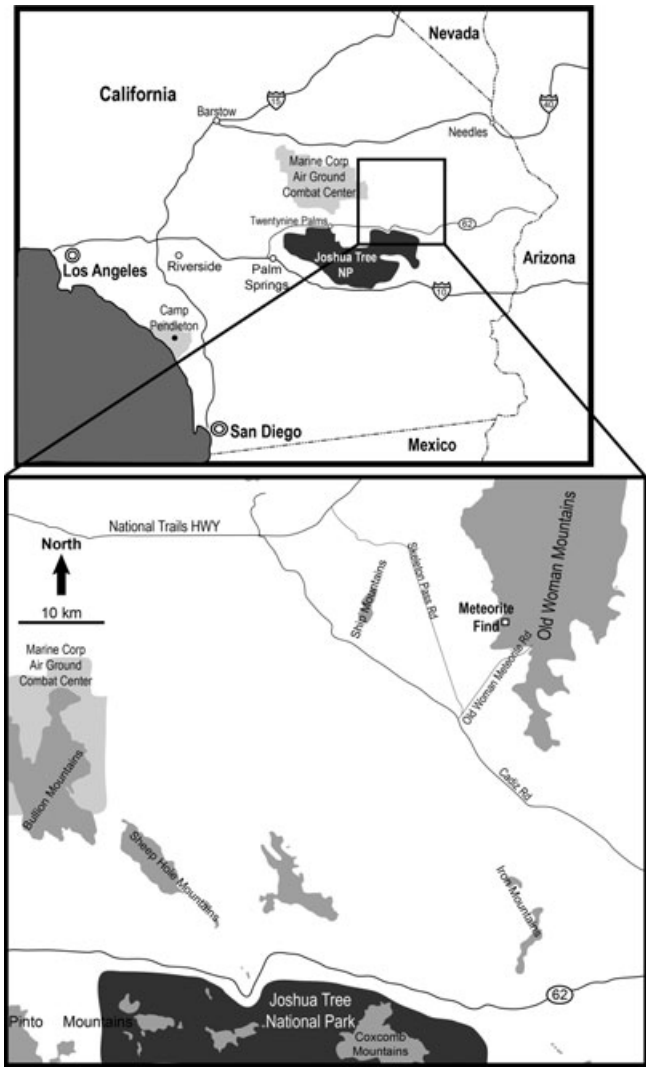

Fig. 1. Map of the region in which the Old Woman meteorite was found. The square box in the top map shows the general area where the Old Woman meteorite was found in mountains in the Mojave Desert, while the blow-up box shows the meteorite's find location in the Old Woman Mountains.

Ni, and therefore concluded that the specimen was not meteoritic.

While the testing at the Griffith Observatory was being undertaken, Friberg sent a letter to the Smithsonian on August 16, asking "if you could give us a value scale for something of this nature & who we might contact to market it" (Friberg 1976). In Meteorite Curator Roy S. Clarke Jr.'s absence (he was out of the country on vacation at the time), Edward P. Henderson, the Curator Emeritus of Meteorites, replied by telegram on August 27 that "Photo shows you probably have an iron meteorite. We are interested. Letter follows" (Henderson 1976). That same day, Division of Meteorites Specialist Al Noonan wrote Friberg to say

Fig. 2. The Old Woman meteorite as it appeared when it was found in March 1976 high up the wash of a canyon in the Old Woman Mountains. The photo was taken in late September, 1976, during Smithsonian Meteorite Curator Roy S. Clarke Jr.'s first visit to the find site.

that its monetary value depended on its type and condition, and requested a fragment be sent to the Smithsonian for study. Friberg sent a small specimen (now cataloged, along with the main mass, as USNM 5924) on August 30, and on September 10 Clarke wrote him, saying that "your specimen is certainly a meteorite. I would like very much to conduct an on the site investigation at the earliest possible date" (Clarke 1976a).

TRIP TO THE OLD WOMAN MOUNTAINS

Clarke quickly made arrangements with Friberg for a trip to California to investigate the meteorite. Before leaving Washington, he learned that much of the land near Twentynine Palms, where he was to meet Friberg, was under the control of various U.S. Government agencies. Since the ownership of meteorites depends on the ownership of the land on which they fall or are found, Clarke realized it was crucial to determine whether or not the meteorite was located on land in the public domain. On the morning of September 20, he met with Friberg and Harwood, and plans were made to leave early the next morning to visit the site of the meteorite. He then visited the administrative office of the nearby Joshua Tree National Monument to inform officials there of his visit. There was also another reason why Clarke wanted to contact government officials prior to going into the field: "I was going into a remote area

where I had no previous experience and with individuals whom I did not know. I wanted responsible government officials to know of this in case of trouble" (Clarke 1978b).

On September 21, Clarke, Friberg, and Harwood travelled to the site of the meteorite in a 1949 four-wheel drive Power Wagon. A good part of the trip was cross country, and they did not arrive at the finders' base camp at the foot of the mountain until 2:00 p.m. It took over 2 h of strenuous hiking up the mountain to reach the meteorite. Once there, Clarke took a series of measurements and photographs. Although he felt very pressed for time, he saw all he needed. On their part, Friberg and Harwood pressed him on how much the meteorite was worth. The group left the meteorite at 5:40, and reached base camp at 7:00 p.m., just as darkness set in (Clarke 1976d). Clarke later recalled that it was perhaps the most beautiful night sky he had ever seen.

Clarke suspected the meteorite was on land under the control of the Bureau of Land Management (BLM), and on September 23 and 24, he visited the Riverside BLM office and informed them of the presence of a large iron meteorite in the Old Woman Mountains. He also told them that the Smithsonian wanted the meteorite if in fact it was located on federal property. Clarke suggested that he go back to the site with Friberg and BLM officials to determine its exact location. He telephoned Friberg, who agreed to meet them at a rendezvous point early on September 27 for a return visit. After returning to Twentynine Palms, Clarke spent the next day in an unsuccessful attempt to trace the mining claim the finders said they had placed on the meteorite.

On the 27th, Clarke went to the BLM office early in the morning, and with two BLM officials drove to the airport for a helicopter pick up. They flew to the agreed upon rendezvous point, a road crossing in the desert, but there was no one there; no person, no car—just road, dirt, and dried grass. After circling around to be sure, they flew to Harwood's house at Twentynine Palms to see if Friburg was there. But again, there were no indications of life. They then flew out to the Old Woman Mountains, where Clarke led them to the meteorite. They found it without much difficulty, and were able to land on a nearby ridge. Time was again limited, but they were able to more positively identify the meteorite's position. After establishing its exact location on maps (34°28′N, 115°14′W) and checking appropriate records, the BLM determined that the meteorite was in fact on federal property (Clarke 1978b).

On October 1, Gerald Hillier, the District Manager of the Riverside BLM office, wrote to Friberg to inform him that on the basis of the September 27 trip, it was determined that the meteorite "is in fact located on national resource lands (Public Domain) owned by the United States." Furthermore, "it is considered an object of antiquity or of scientific interest and as such comes under the protection of the Antiquities Act of 1906 … [This law] reserve[s] the jurisdiction and control of such objects as found on government land to the Federal Government" (Hillier 1976). Clarke wrote Friberg explaining that he was aware "… this is not the interpretation that you were hoping to receive. It does not surprise me, however, and I tried to prepare you for it" (Clarke 1976b). On the very day Clarke wrote this letter, he found out that the reason why Friberg hadn't shown up on the morning of September 27 as agreed was that he had gone to see a lawyer (Clarke 1976c). This set the stage for events that would embroil the meteorite in several years of heated disputes and make the meteorite one of the most controversial in the modern era (Table 1).

THE QUESTION OF THE METEORITE'S OWNERSHIP

The ownership of meteorites has often been a controversial issue, one that has been litigated in celebrated court cases in the United States and elsewhere. In the United States, the courts have held that meteorites typically belong to the owner of the land on which they fall or are found, not the finders. Precedent was set in 1892 in the case of the Forest City meteorite, when the Iowa Supreme Court upheld the landowner Goddard over Winchell, who had been sold the meteorite by the finder. This was followed in 1905 by the case of the Willamette meteorite, the largest found in the United States, when the Oregon Supreme Court upheld the landowner Oregon Iron Company over the finder Hughes (Schmitt 2002). Since the Old Woman meteorite had been found on federal land, the Antiquities Act vested ownership in the federal government, not in the finders.

In an attempt to gain control of the meteorite, the finders filed a placer mining claim on the land where it was situated. But they were notified by the District Manager of the Riverside BLM in early October that "Your mining claim … authorizes the removal of only locatable minerals. Meteorites are not locatable since objects of this nature do not constitute a valuable mineral deposit within the meaning of the United States' mining laws" (Hillier 1976). Precedent for this had been established as early as 1908, in the case of an alleged 91 metric ton meteorite found on federal land in the Washington Forest Reserve, when the Chief, Forest Service, ruled that "A placer location made for the sole purpose of embracing the area where such meteorite may

Table 1. Abbreviated chronology of important dates in the Old Woman meteorite controversy, 1976–1980

March, 1976	Old Woman meteorite found.
September 21, 1976	R. S. Clarke Jr. visits site.
October 1, 1976	BLM informs finders meteorite is on federal land.
November 4, 1976	Smithsonian formally requests BLM to transfer meteorite to it.
December 21, 1976	Dept. of Interior grants Smithsonian's request.
May 5, 1977	Dept. of Defense grants U.S. Marines authorization to airlift meteorite from mountain.
June 17, 1977	Meteorite airlifted from mountain.
June 24, 1977	Old Woman meteorite accessioned into Smithsonian's National Collection.
June 29, 1977	Finders file request in Federal District Court for temporary restraining order to keep meteorite in California.
July 20, 1977	San Bernardino County Museum and State of California file suits in Federal District Court against removal of meteorite from California.
August 22, 1977	Suit brought by finders dismissed with prejudice.
September 7, 1977	Sec. of Interior announces meteorite will stay in California.
Sept.–Nov., 1977	Representatives from Smithsonian, Dept. of Interior, and State of California attempt to reach agreement on how meteorite could be exhibited in designated institution there.
December 27, 1977	Suits brought by San Bernardino County Museum and State of California denied.
March 8, 1978	Old Woman meteorite arrives at Smithsonian for study and cutting.
May 1978	San Bernardino County Museum and State of California appeal denial of their suits.
July 1978	San Bernardino County Museum and State of California seek injunction from Federal District Court enjoining Smithsonian from cutting meteorite until ruling from U.S. Court of Appeals handed down.
August 23, 1978	Injunction sought by San Bernardino County Museum and State of California denied. This decision is appealed.
March 23, 1979	Smithsonian drafts formal loan agreement to display meteorite at BLM way station in Barstow, California for 3 years.
April 2, 1979	Injunction sought by San Bernardino County Museum and State of California again denied.
June 5, 1979	First piece, weighing 4.66 kg, removed from meteorite.
May 9, 1980	First big cut, 427.3 kg, completed.
May 15, 1980	U.S. Court of Appeals upholds Federal District Court's decision against San Bernardino County Museum and State of California.
September 27, 1980	Old Woman meteorite placed on exhibit at BLM's Desert Discovery Center in Barstow, California.

be would not be valid, if the ground contained no other value than the meteorite" (Ringland 1908).

Such a ruling had been affirmed in 1944, when Smithsonian Curator Henderson enquired if its acquisition of the Drum Mountains meteorite, found by Japanese-Americans interned on federal lands in the Utah desert, could be contested under a mining claim. The Assistant Secretary of the Department of the Interior informed him that if meteorites have a market value only for the reason that they are meteorites and not because of their mineral content, they are not subject to mining laws (Chapman 1944). Accordingly, the BLM District Manager told the finders of the Old Woman meteorite that under the powers of the Antiquities Act, the jurisdiction and control of the meteorite would be transferred to the Smithsonian Institution (Hillier 1976).

Since ownership of the meteorite was granted to the Smithsonian under the powers of the Antiquities Act, a ruling that was subsequently vigorously contested, it will be useful to examine in some detail exactly how this Act applied. Passed by the 59th Congress on June 8, 1906, the main purpose of the Antiquities Act (34 Stat. L., 225) was to protect archeological sites in the American southwest from looting. The act gave the Secretaries of the Departments of the Interior, Agriculture, and War the right to grant permits for the examination of ruins, the excavation of sites, and the gatherings of "objects of historic or scientific interest" on federal lands under their respective jurisdictions. Permits could be granted to scientific or educational institutions which they deemed properly qualified, provided that the gatherings of these objects be for permanent preservation in public museums.

On December 28, 1906, the three secretaries prescribed further rules to carry out the provisions of the act. Among other things, these Uniform Rules and Regulations granted the secretaries not only the right to grant permits for the gathering of objects of historic or scientific interest, but jurisdiction over the objects as well. Furthermore, it stipulated that all permits granted by the secretaries "shall be referred to the Smithsonian Institution for recommendation."

Two things are important to bear in mind here. First, although meteorites were not specifically mentioned in the Antiquities Act, they were considered to fall under its purview since they were considered to be "objects of scientific interest." Second, since the BLM was under the Department of the Interior, the Act granted the Secretary of the Department of the Interior jurisdiction over any meteorites found on its land. Since the Old Woman meteorite had been found on BLM land, it fell under his jurisdiction.

In the case of the Old Woman meteorite, there thus seemed little question that jurisdiction and control of it could be transferred to the Smithsonian under the powers of the Antiquities Act. The decision to do so, however, came under heavy fire from two quarters—from lawyers in San Bernardino, California representing the finders, and from John Wasson, a professor of geochemistry and chemistry at the University of California, Los Angeles (UCLA). Wasson had been sent a small specimen of the meteorite in early October 1976 through Bekins Mineral Resources in Altadena, California, a company that worked with prospectors, and was apparently helping to finance the three prospectors in their endeavors. Wasson had determined that the specimen was a genuine meteorite, and with his colleague John Willis quickly prepared a talk to be given at the Meteoritical Society meeting in Bethlehem, Pennsylvania later that month (Wasson and Willis 1976). In discussion with Clarke, Wasson made it clear that he wanted the meteorite to remain in California. On November 4, 1976, Smithsonian Secretary S. Dillon Ripley formally requested the State Director of the BLM in Sacramento that the meteorite be transferred to the Smithsonian and accessioned into the National Meteorite Collection (Ripley 1976).

In mid November, Wasson wrote Clarke to suggest that the meteorite be cut, and a "representative sample (say 5–10%)" be transferred to the Smithsonian, with the main mass remaining in California—preferably at UCLA, or if that was not possible, at the Los Angeles County Museum of Natural History or the Griffith Observatory (Wasson 1976a). Wasson also wrote the two California senators, Alan Cranston (Wasson 1976b) and John Tunney (Wasson 1976c), requesting their help in keeping the meteorite in southern California. He pointed out that if the meteorite was transferred to Washington, the great majority of California residents would never be able to see it, and that Californians had recently "lost" the Goose Lake meteorite, which had been found on federal land in the Modoc National Forest in northeast California, to the Smithsonian. Wasson noted that "as I see it, the main question is of a political rather than legal nature … It was surely not the intention of the congress [in passing the Antiquities Act] that all meteorites found on government lands should be exhibited … in Washington rather than exhibited in the other fine public institutions of this country." Wasson's letters served as a catalyst, and played a role in the state of California's entry into the dispute.

On December 21, the Director of Administrative Services, Office of the Secretary of the Department of the Interior, responded to Secretary Ripley's request, and granted the necessary authorization: "By this letter you are authorized and permitted to begin operations for the recovery of the Old Woman Mountains meteorite and for its transfer to the Smithsonian Institution where it will be available for scientific study and public exhibition" (Carpenter 1976).

With proper authorization from the Department of the Interior, the Smithsonian moved forward with plans to remove the meteorite from the mountainside and transfer it to Washington. Realizing that there was a Marine Corps base at Twentynine Palms, some 80 km from the site, Smithsonian officials focused on the idea of having them do the transport by helicopter. They responded that they could do the job, but needed authorization from the Secretary of Defense to undertake it. On January 11, 1977 Secretary Ripley wrote the Secretary, Donald H. Rumsfeld, seeking the necessary authorization (Ripley 1977a). Unfortunately, the request was made at the time the Ford Administration was transitioning to the Carter Administration, and the carefully prepared groundwork was ignored. As a consequence, the reply from the Assistant Secretary denied authorization on the grounds that Department of Defense did not utilize military transport when commercial carriers able to do the job were available (Riley 1977). A tense several months of seeking alternatives ensued.

In April, Arizona Senator Barry Goldwater, a Regent of the Smithsonian, wrote the new Secretary of Defense, Harold Brown, repeating the request for military assistance, pointing out that the only private helicopter service capable of carrying out the transfer was in Oregon, so far distant from southern California that the Smithsonian couldn't afford its services (Goldwater 1977). This was followed a week later by a similar letter from Secretary Ripley (1977b). These letters proved successful, and the Deputy Secretary of Defense granted authorization for the Marines to remove the meteorite from the mountain (Dumauf 1977). Plans were drawn up for the Marines to airlift the meteorite on June 17, following which it would be put on display at the BLM's Riverside office for 2 weeks, and then shipped to the Smithsonian for study.

REMOVAL OF THE METEORITE FROM THE MOUNTAIN

Clarke arrived back in California on June 13, 1977 and spent the next few days at the Riverside BLM office, where joint preparations with BLM and U.S. Marine

Fig. 3. Roy S. Clarke Jr. with the Old Woman meteorite during his return visit to the find site to witness the meteorite's removal from the mountains on June 17, 1977. By then, the meteorite had been moved slightly by its finders from its original position. Photo credit: Joe Goodwin.

Fig. 4. Riggers from the First Marine Division Landing Support Co. at Camp Pendleton use jacks and timber to maneuver the meteorite so that a double thickness of cargo net can be placed under it and it can be airlifted by helicopter from the mountains. The photo was taken by Joe Goodwin at 3:00 p.m. on June 16, 1977.

Corps representatives were made for removing the meteorite and accommodating the press. On the afternoon of the 15th, Clarke and the BLM group moved to Needles to be nearer the field site, and arrived on the mountain by helicopter the next day to confer with BLM representatives and the Marine Corps detail, and observe the lift (Clarke 1977b) (Fig. 3).

Moving the meteorite was a major operation. On the morning of June 16, a seven-man helicopter support team from the First Marine Division Landing Support Co. at Camp Pendleton was flown in to the foot of the mountain. After a trek of 2 1/2 h up the dry wash, the team reached the meteorite. Shortly after their arrival, a helicopter from the Marine Heavy Helicopter Squadron 363 lowered a bundle to them containing cargo nets, hydraulic jacks, timbers, water, and C-rations. For the next several hours, the Marine riggers used the jacks and timbers to wrestle the meteorite free from where it was wedged between two boulders, and slip a double thickness of cargo net under it (Fig. 4). They then sought a shady place amongst the boulders to bed down for the night (Navy Times 1977). On the following morning, one of the Squadron's CH-53 helicopters dropped a 25 m cable down to the Marines, who attached it to the bundled meteorite. The helicopter then carefully lifted the meteorite from its resting place, and gently set it down a short time later on a desert road 19 km away (Evans 1977) (Fig. 5).

Present on the road were more than 40 representatives of local and national news media, members of the press, representatives from the Riverside BLM office, Marines, the meteorite's three finders, and Wasson (Clarke and BLM representative Joe Gulliksen arrived from their vantage point on the mountain some time after the meteorite arrived). According to a newspaper account of the event (Alexander 1977), an uneasy scene developed as the crowd gathered around the meteorite, and opposing views about the meteorite's ownership and disposition were strongly voiced. But with proper authorization from the Department of the Interior, the meteorite was fork lifted onto a truck and transported to the BLM District Office in Riverside. Clarke spent the following 3 days in Riverside, engaging in conversations with visitors to the exhibit and members of the press, and conferring with BLM representatives.

At a weigh station en route, the meteorite was taken off the truck and weighed; at 2753 kg, it was the second-largest meteorite ever found in the United States (after Willamette). Removed from the truck and away from the crowd that had earlier been gathered around it, the Old Woman meteorite could be carefully observed in its entirety for the first time. The meteorite's mass is semi-equant with an irregular surface, measuring $0.8 \times 0.9 \times 1.0$ m. Its exposed upper surface when found exhibited a relatively smooth texture on one side, while the other side was pitted reminiscent of regmaglypts. Superimposed on this pitted surface were cylindrical indentations probably formed by preferential ablation of

Fig. 5. A CH-53 helicopter from Marine Heavy Helicopter Squadron 363 begins to lift the meteorite from its resting place in the Old Woman Mountains on June 17, 1977. The meteorite, safely bundled in its cargo net cocoon, hangs from the end of a 25 m cable. Photo credit: Joe Goodwin.

a less resistant phase, and subsequently enlarged and deepened by weathering produced during pooling of rainwater. When the meteorite was moved, the bottom surface, which had been in contact with soil, exhibited a thin, irregular coating of caliche.

THE DISPUTE MOVES TO THE COURTS

Far from settling the issue, the removal of the meteorite from the Old Woman Mountains only served to intensify the battle over it. In June, letters to the Smithsonian from Wasson (Wasson 1977) and the San Bernardino County Museum (Smith 1977) requested that the meteorite be put on permanent exhibition in California, and California Congresswoman Shirley Pettis, the Representative of the district where the meteorite had been found, requested that either the entire meteorite or a portion of it be housed in a museum in her district (Pettis 1977). Clarke accessioned the meteorite into the Smithsonian's National Collection on June 24, while it was still on display in California (Clarke 1977a).

Fig. 6. Fascinated children gleefully touch the visitor from outer space. Hundreds of persons came to see the hotly contested Old Woman meteorite when it was placed on temporary exhibit at the Bureau of Land Management District Office in Riverside, California following its removal from the mountains. The photo was taken in mid- to late-June, 1977.

By now, the Old Woman meteorite had become something of a cause célèbre, and hundreds of persons came to see it at the Riverside BLM office (Fig. 6). To provide an additional opportunity for more persons to see it, the Smithsonian and the BLM agreed on plans to continue its display there for an additional week, and then to have it placed on display for 1 week each at the San Bernardino County Museum and the Los Angeles County Museum of Natural History. After these display periods, the meteorite would be returned to the BLM Riverside office, then shipped to the Smithsonian.

Before the agreed-upon return date arrived, however, the three finders took the matter to court. Before Judge Francis Whelan in the Federal District Court in Los Angeles, they filed a suit on June 29, 1977 against the BLM, the Department of the Interior, Secretary Ripley, et al., requesting a temporary restraining order to keep the meteorite in California, arguing they owned it on the basis of their mining claim. The Smithsonian and the Department of the Interior were represented in the suit by the Department of Justice. Judge Whelan denied the temporary restraining order, claiming that there was no immediate and irreparable harm warranting the issuance of such an order. This case would be the first of several that would ultimately be filed in the courts.

Increasing pressure was quickly brought to bear upon the Smithsonian to allow the meteorite to remain in California. On July 11, Giles Mead, the Director of the Los Angeles County Museum of Natural History, wrote Secretary Ripley that "The exploitive removal of

objects from point of origin to institutions thousands of miles away with arrogant disregard for local argument and reasonable claim takes on an unpleasant odor. … This is not the nineteenth century.'' He went on to request that the Smithsonian ''cede all presumed title'' to the meteorite to either his museum, the San Bernardino County Museum, or UCLA (Mead 1977).

Pressure was also brought to bear upon Cecil Andrus, the Secretary of the Department of the Interior. On July 12, the Secretary for Resources for the State of California wrote Andrus acknowledging ''the probable legitimacy of the ownership claim of the United States,'' but claiming that the Antiquities Act, ''if applicable at all to meteorites, clearly allows the display of the Meteorite in any public museum.'' He therefore suggested that Andrus find an arrangement whereby the Smithsonian retained its ownership interest in the meteorite, but allowed it to go on permanent display in the Los Angeles County Museum of Natural History (Johnson 1977).

A week later, Ripley received a letter from California Representative George E. Brown signed by virtually the entire California Congressional Delegation, urging him to ''speed arrangements for [the meteorite's] permanent display in California'' (Brown 1977). In response, Ripley assured them that the Smithsonian was ''certainly fully aware of the interests of the State of California,'' and that once the museum cut the meteorite for study, a portion would be sent to an appropriate museum in California (Ripley 1977d). In addition, the museum would be sent a cast of the whole meteorite.

At the same time, in a letter to Wasson, Ripley took pains to make the Smithsonian's position clear. He outlined the Smithsonian's long involvement with meteorites and the steady growth of the National Collection, and its extensive usage by the national and international scientific community. He went on to point out the high quality of the museum's professional and support staff, as well as its laboratory and shop facilities. For these reasons, the Smithsonian ''had a responsibility to involve itself with the Old Woman Mountains meteorite.'' But he assured Wasson that the museum was ''certainly mindful of the legitimate interests of the California institutions, just as we are of our own national and international obligations,'' and that a replica of the meteorite and a polished slice would be sent to an appropriate California museum on a long-term loan (Ripley 1977c).

On July 20, 1977, the very day that Ripley wrote Wasson, the San Bernardino County Museum and the State of California filed separate suits (later joined) in the Federal District Court in Los Angeles, against the BLM, the Department of the Interior, Secretary Ripley, et al., seeking a preliminary injunction against removal of the meteorite from California and title to it, alleging various statutory violations. Basically, they contended that the Department of the Interior had violated the Antiquities Act by discriminating in favor of the Smithsonian in permitting it to take custody of the meteorite. This time, the court granted a temporary restraining order to keep the meteorite in California until such time as it made a declarative judgment on the question of its ownership. It requested the parties involved to engage in intensive settlement discussions to try to work out their differences.

During the time that the matter was before the court, the San Bernardino County Museum sent Andrus a letter similar to the one he had received from the Secretary for Resources for the State of California, requesting him to reconsider the decision to place the meteorite in the Smithsonian, and allow it to be permanently housed in the San Bernardino museum. On July 28, Senator Alan Cranston wrote a strong letter to Andrus, disputing that the Antiquities Act was a viable legal basis for the federal ''seizure'' of the meteorite, and suggesting that its removal was ''an affront to common courtesy and to the desires of countless Californians and others in the West to retain custody of the meteorite …'' He requested that if the court ruled that the U.S. did have legal title to the meteorite, Andrus ''forgo exercising that right and agree to permit the Old Woman meteorite to remain in California with an appropriate museaum [sic] or scientific institution'' (Cranston 1977).

On August 22, 1977, the Smithsonian received some welcome news from the Department of Justice attorney representing the defendants in the June law suit filed by the finders. Judge Whelan had signed an order dismissing the suit brought about by the three finders of the Old Woman Mountains meteorite. The suit was dismissed with prejudice.

When combined with the strong protests being made by Representative Pettis, the California Congressional Delegation, the Secretary for Resources for the State of California, the San Bernardino County Museum, the Los Angeles County Museum of Natural History, the State of California, Senator Cranston, Wasson, and others, Judge Whelan's ruling quickly prompted a dramatic move on Secretary Andrus's part. On September 7, his office in Washington, D.C. dropped a bombshell: ''California will get to keep the Old Woman Meteorite. Interior Secretary Cecil D. Andrus decided to grant custody of the three-ton rock to the state in which it was found over a year ago, turning down a bid by his own agency [through the Director of Administrative Services, Office of the Secretary of the Interior] to [grant Secretary Ripley authorization to] haul it back to Washington for display in the Smithsonian Institution'' (Norton 1977). A short article in the *New York Times* dated September 8 went on to say that ''Although the meteorite will stay in

California, it remains the property of the Federal Government under a 1906 Antiquities Act that the Interior Department contends gives it custody."

Andrus's decision served as a game-changer. Recall that prior to his announcement, the Department of the Interior had transferred right and title to the meteorite to the museum; the suit brought by the finders of the meteorite had been dismissed with prejudice by the Federal District Court in Los Angeles; and it had been accessioned into the National Collection of Meteorites. The Smithsonian believed that it had ownership of the meteorite, and had formulated plans to keep the main mass, but had agreed to provide a California museum with a cast of the meteorite and a polished slice after conducting its scientific study.

Although the Smithsonian did not think Andrus had legal justification for such a decision at this late stage of the game, and felt it could have refused to honor his ruling (Taylor 1981), it made the political decision to acquiesce, and offered to ship the main mass of the meteorite—not just a slice—to a California museum after it had completed its study.

In the weeks that followed, the court-ordered settlement discussions took place. The Smithsonian worked with the Department of the Interior and the Department of Justice to arrive at terms and conditions upon which an agreement could be implemented between the Smithsonian and the State of California to exhibit the meteorite in a designated museum or institution there. Attorneys from these three parties met on September 21. On the day following the meeting, the Smithsonian reported to the Department of Justice that it agreed to the following stipulations as part of a proposed consent decree: the United States possesses all right, title, and interest in the Old Woman meteorite; the [Office of the] Secretary of the Department of the Interior acted properly in transferring custody and control of the meteorite to the Smithsonian under the Antiquities Act; and the United States will negotiate for long-term display of the meteorite within the state of California (Challinor 1977).

In its report to the Department of Justice on September 28, the Department of the Interior voiced its support of these stipulations, and stated further that it had no objection to the Smithsonian's plan to bring the meteorite to Washington for a short period of time, not to exceed 1 year, for scientific analysis prior to releasing it to California. Its only concerns were that the meteorite's display and scientific value not be diminished in this process, and that the meteorite be returned as promptly as possible (Webb 1977).

On October 17, attorneys from the three parties met again, joined this time by the Deputy Counsel, County of San Bernardino and an attorney from the California Attorney General's Office. In a follow-up letter to the Department of Justice on November 14, the California attorneys also agreed with the stipulations set out by the Smithsonian and agreed to by the Department of the Interior, but proposed that a five-member committee be set up, composed of Wasson, Clarke, and three other members agreed to by the parties. This committee, by majority vote, would make the final decision "as to what cutting, if any" would be done on the meteorite.

The California attorneys further called for the establishment of a Joint Powers Agreement, under which persons from the County of San Bernardino, the County of Los Angeles, and the Board of Regents of the University of California would form a three-member committee. The committee would investigate the possibility of displaying the meteorite in a museum in California, and would be authorized to loan the meteorite to other reputable museums for short-term displays, while the Joint Powers Agreement would recognize that the "permanent home" of the meteorite would be in San Bernardino County, where the meteorite had been found (Younger et al. 1977).

On December 27, 1977, Judge Whelan announced his decision on the consolidated suit that had been brought by the State of California and the San Bernardino County Museum in July. He noted that he had delayed ruling on the motions thinking the parties would settle their differences, but it was now apparent they could not. Although he recognized how culturally satisfying it would be to the people of southern California to have the meteorite remain there, the law was clear: the meteorite had been found on federal land, and therefore belonged to the United States; the Secretary of the Department of the Interior has the authority under the Antiquities Act to issue permits for the gathering of objects of scientific interest found on federal lands under his jurisdiction; and the Secretary did not err in permitting the Smithsonian to take possession of the meteorite. He therefore denied the motions for preliminary injunction against removal of the meteorite from California and title to it, and vacated and set aside the temporary restraining order to keep the meteorite in California.

In January and February of 1978, the Smithsonian met with members of the staff of Representative Pettis and Senator Cranston, explaining that it was the Smithsonian's intention to have the meteorite sent to Washington for study, during which "a slice of up to one-third" would be removed for scientific examination. Following that, it would be returned to a museum in California. With Cranston's agreement, plans were drawn up to have the meteorite sent on March 3 to the Smithsonian from the BLM way station in Barstow, California, where it was then being held (Taylor

undated). These plans were announced in a Smithsonian news release on March 2. As well, Lawrence E. Taylor, the Smithsonian's Coordinator of Public Information, spoke over the phone with several California reporters in an effort to make the Smithsonian's position as clear as possible, and Secretary Ripley sent letters explaining the plan to every member of Congress from California. The meteorite arrived at the Smithsonian's National Museum of Natural History on March 8, 1978—2 years after its discovery, and 9 months after its removal from the Old Woman Mountains.

To ensure that the eventual exhibition of the meteorite would be consistent with the wishes of Californians, the Smithsonian asked Senator Cranston's staff to help select a museum where a long-term loan arrangement could be made (Taylor undated). Eventually, his staff recommended the Los Angeles County Museum of Natural History, which the Smithsonian had been leaning towards because of their long history of collaboration (Ripley 1977c).

Two other problems soon arose. In May, the San Bernardino County Museum and the State of California appealed Judge Whelan's ruling of December 27, 1977 dissolving the temporary restraining order and denying the request for a preliminary injunction. The Department of Justice informed the Smithsonian that any decision from the U.S. Court of Appeals for the Ninth Circuit could take up to 2 years or more. Secondly, on the same day that Giles Mead, Director of the Los Angeles museum, was sent a proposed exhibit agreement, John Wasson again stepped forward. Responding to the Smithsonian's March 2 news release that it intended to remove a slice of about one-third of the meteorite for its study, he wrote Senator Cranston and others, claiming that "the chief motive of the Smithsonian is to retain the largest amount of the Old Woman that they can without obviously going against the declaration [of] Secretary Andrus," and that its cutting plan would seriously detract from the exhibit value of the main mass.

He went on to urge that letters be written to Secretaries Andrus and Ripley requesting that no cutting of the meteorite be carried out until the Smithsonian submitted detailed plans, prepared a position paper comparing the scientific and exhibit-related pros and cons of its proposed plan, and invited comments from several curators and iron meteorite researchers regarding the merits of its plan and Wasson's own plan. Wasson argued that "The chief scientific value to be obtained by sawing the Old Woman is to find out whether the entire 2753 kg mass was earlier a single gamma phase crystal with maximum dimensions of about 110–120 cm," and that this question could be answered by measurements on small parallel cuts made on opposite sides of the meteorite, involving the removal of only "a few tens of pounds" (<20 kg) of material (Wasson 1978a). As earlier, Wasson's letters served as a catalyst, and played a role in the decision of the State of California and the San Bernardino County Museum to ask the Federal District Court in Los Angeles in July to enjoin the Smithsonian from cutting the meteorite prior to a ruling by the U.S. Court of Appeals for the Ninth Circuit.

DEBATE OVER THE CUTTING OF THE METEORITE

Sensitive to Wasson's letters and the Court's injunction, and desirous of formulating the best research plan possible, in September 1978 Clarke sent a "Dear Colleague" letter to 19 individuals whose research either involved iron meteorites or who were curators or administrators of museums with meteorite collections, soliciting their views on how the Old Woman meteorite should be studied (Clarke 1978a). The letter was written to encourage a broad range of responses, and did not mention either the Smithsonian's position or Wasson's.

Wasson responded with a "Dear Colleague" letter of his own. After informing the recipients of the "political tug-of-war [that] is in progress between the Smithsonian Institution and the State of California," he informed them their response to Clarke would have "implications regarding the amount of material that is to remain in Washington." After making sure they realized that, he went on to request that they provide him with a copy of their response "in order to confirm that the amount to be removed seems reasonable from the viewpoint of Californians" (Wasson undated).

Responses to Clarke's "Dear Colleague" letter were generally favorable to the Smithsonian's position. Vagn Buchwald, for example, pointed out that Old Woman appeared to be transitional between group IIA and IIB meteorites, with a structure that would probably correspond to that of such large irons as Navajo, Mount Joy, and Sikhote-Alin. Since only relatively small sections of these meteorites were available to researchers, however, a large section through Old Woman would provide a unique opportunity for study (Buchwald undated).

Specifically, as Joe Goldstein pointed out, a large surface area would provide an opportunity to observe chemical and structural features that could yield unique data about conditions during the solidification of the parent iron meteorite. Since such information about early high temperature events in the formation of iron meteorites was severely lacking, a large cut and polished surface of Old Woman could provide incalculable scientific information (Goldstein 1978). It was also noted that the Smithsonian was the only meteorite laboratory

in the United States with the equipment and expertise necessary to make such a large cut.

Interestingly, individuals other than Wasson who were opposed to the idea of a large cutting of the meteorite did not respond to Clarke directly, but instead submitted affidavits directly to the U.S. Court of Appeals for the Ninth Circuit. The main argument against the Smithsonian plan was that a removal of one third of the mass of the Old Woman meteorite, the second largest ever found in the United States, would greatly reduce its exhibition value. Basically, they agreed with Wasson that a much smaller cut of the meteorite, no more than a slice of ~23 kg, would suffice for scientific research purposes (Wasson 1978b). It is perhaps worth noting that four of the six strongest opponents of a large cut—Wasson; Peter Keller, the curator of mineralogy and geology at the Los Angeles County Museum of Natural History; Gerald Smith, the director of the San Bernardino County Museum; and Leon Silver, professor of geology at the California Institute of Technology—were from California.

As a museum curator, Clarke was certainly sympathetic to the arguments about the Old Woman's exhibition value, but believed that they played a secondary role to scientific considerations (Clarke 1979c):

> I would like to … comment on our responsibility as a repository of meteorite material. Our first responsibility is to the science, to see that these precious planetary system samples that come our way are studied as broadly and as imaginatively as possible. Conservation of material is essential and exhibit value is important. Public exhibit, however, must be a secondary consideration until material is secured for scientific needs.

On August 23, 1978, the Federal District Court in Los Angeles denied the injunction against allowing the meteorite to be cut until a ruling had been handed down by the U.S. Court of Appeals for the Ninth Circuit. This decision was appealed, but the injunction was again denied in an order filed on April 2, 1979. These rulings opened the way for the Smithsonian to cut the meteorite and begin its scientific study.

On May 21, Clarke outlined the Smithsonian's cutting plan. A small ~2 kg piece would be removed first to provide a view of the interior of the meteorite. A slice would then be removed from this for macro etching, and pieces would be taken for metallographic examination and bulk chemical analysis for both major and trace elements. Information gleaned from this would play a critical role in developing plans for the detailed study of the meteorite. Following this, a major cut would be made separating the meteorite into a research piece and an exhibit piece. When completed, the exhibit piece would be shipped to California for display in a museum (Clarke 1979b).

Fig. 7. Tim Rose, Museum Technician, with the Old Woman meteorite in the National Museum of Natural History's Materials Processing Laboratory shortly after the first big cut, 427.3 kg, had been completed on May 9, 1980. Photo credit: Chip Clark (Smithsonian).

Cutting began a week later, on May 29. The first piece (USNM 6358), weighing 4.66 kg, was removed on June 5 and then ground, polished, and etched. Four polished sections were subsequently prepared from this material for metallographic examination. Although 15% of its surface exhibited the structure of a coarsest octahedrite, the remainder of the surface was essentially one large kamacite crystal, indicating a hexahedrite classification. This led Clarke to comment (Clarke 1979d) "It appears that [we have] a new transitional type meteorite on our hands … It is obvious that we are involved with an unusually coarse structured meteorite. Knowing this, I am more confident than before that a major cut is essential."

Work began on the major cut on August 10. It was a slow, tedious, and exacting process which continued into May 1980. Eighty-eight wires were utilized during 124 h of cutting, which took place over a period of 50 days. The result was the removal on May 9 of a large piece from the deeply weathered bottom side (as found) of the meteorite (Fig. 7). The ~70 by 90 cm (0.47 m^2) section weighed 427.3 kg, representing about 15% of its 2753 kg. In the late summer of 1980, the Old Woman meteorite was placed on temporary exhibit for several weeks in the National Museum of Natural History (Fig. 8), while final preparations were being made for its transfer back to California. "This will become a famous meteorite among scientists," Clarke predicted, "and will continue to generate interest for years to come" (Smithsonian Institution News 1980).

Fig. 8. Following the 427.3 kg cut, the Old Woman meteorite was placed on temporary exhibit at the National Museum of Natural History in late summer of 1980. The meteorite rests on its cut surface, and the light patch visible in its center is where the first piece (4.66 kg) had been removed. Photo credit: Victor Krantz (Smithsonian).

THE METEORITE'S RETURN TO CALIFORNIA

Even while the injunctions against allowing the meteorite to be cut were still before the court, the Smithsonian tried to finalize loan arrangements for the eventual display of the main mass in a California museum once it was returned to the state. By then, Giles Mead was no longer the director of the Los Angeles County Museum of Natural History. Although the acting director expressed interest in having the meteorite put on display in the museum, he expressed his "significant objection" to the Smithsonian's plan to cut approximately one-third of the specimen for its research purposes (Arnold 1978). In December 1978, Taylor wrote to the Los Angeles museum and to Senator Cranston's staff, with whom the Smithsonian was in ongoing contact, that "we must reluctantly conclude that under the circumstances the museum is not interested in entering into a loan agreement now," and that discussions with other interested California museums should be begun (Taylor 1978).

In January, 1980, the litigation in which the San Bernardino County Museum and the State of California claimed title to the meteorite reached the procedural stage of oral argument on the merits before the U.S. Court of Appeals for the Ninth Circuit. On May 15, 1980, that court affirmed the Federal District Court of Los Angeles' decision of December 27, 1977, holding that the earlier dismissal of the claims was correct since the plaintiffs failed to state a claim upon which relief could be granted. That decision was not appealed; the long, embattled saga of the Old Woman meteorite had finally come to an end.

Through a loan agreement worked out between the Smithsonian and the Department of the Interior, the main mass of the Old Woman meteorite, now ~2330 kg, was returned on September 27, 1980 to Barstow, California, where it had been kept before it was sent to Washington. It was placed on long-term exhibit at the Bureau of Land Management's Desert Discovery Center, in a ceremonial program headed by Representative Jerry Lewis, who had replaced Shirley Pettis. This ended the meteorite's long odyssey, begun some four and one-half years earlier. As Clarke pointed out, when the Old Woman meteorite was accessioned into the National Collection, it represented "our largest specimen in over 180 years of combined Smithson-Smithsonian meteorite collecting. On occasion I have felt that it has consumed as much effort from as many individuals as the rest of our meteorite specimens combined" (Clarke 1979a).

METALLOGRAPHIC STRUCTURE OF THE OLD WOMAN METEORITE

Some 35 years after its recovery, the Old Woman meteorite remains a highly unusual example of the metallographic structures observed in iron meteorites, and the value of having a large slice available for examination has been borne out. While the small mass removed initially suggested the presence of two structural types within Old Woman, the metallographic study of the large slice provides invaluable insights into the meteorite's formation.

The 427.3 kg butt end was subsequently divided into a 207 kg butt end (USNM 6360) and a 174 kg research slice (USNM 6359). This 174 kg research slice has been extensively subdivided. Initial sampling included drilling cuttings for cosmogenic nuclides and sampling from three corners of the research slice, with removal of ~1/2 the thickness of the research slice of areas of ~30, 50, and 200 cm^2. Two of these (labeled USNM 6359A and C) sample the hexahedrite portion, while the third (USNM 6359B) samples the octahedral structure. Numerous subsamples and polished sections were prepared from these three pieces. The research slice has been subsequently subdivided, producing a thinner complete slice and a partial slice which was again extensively subsampled. In total, a surface area of ~1.5 m^2 has been examined from the Old Woman meteorite. Examination of a complete slice (Fig. 9) reveals a polycrystalline mass with grain sizes ranging

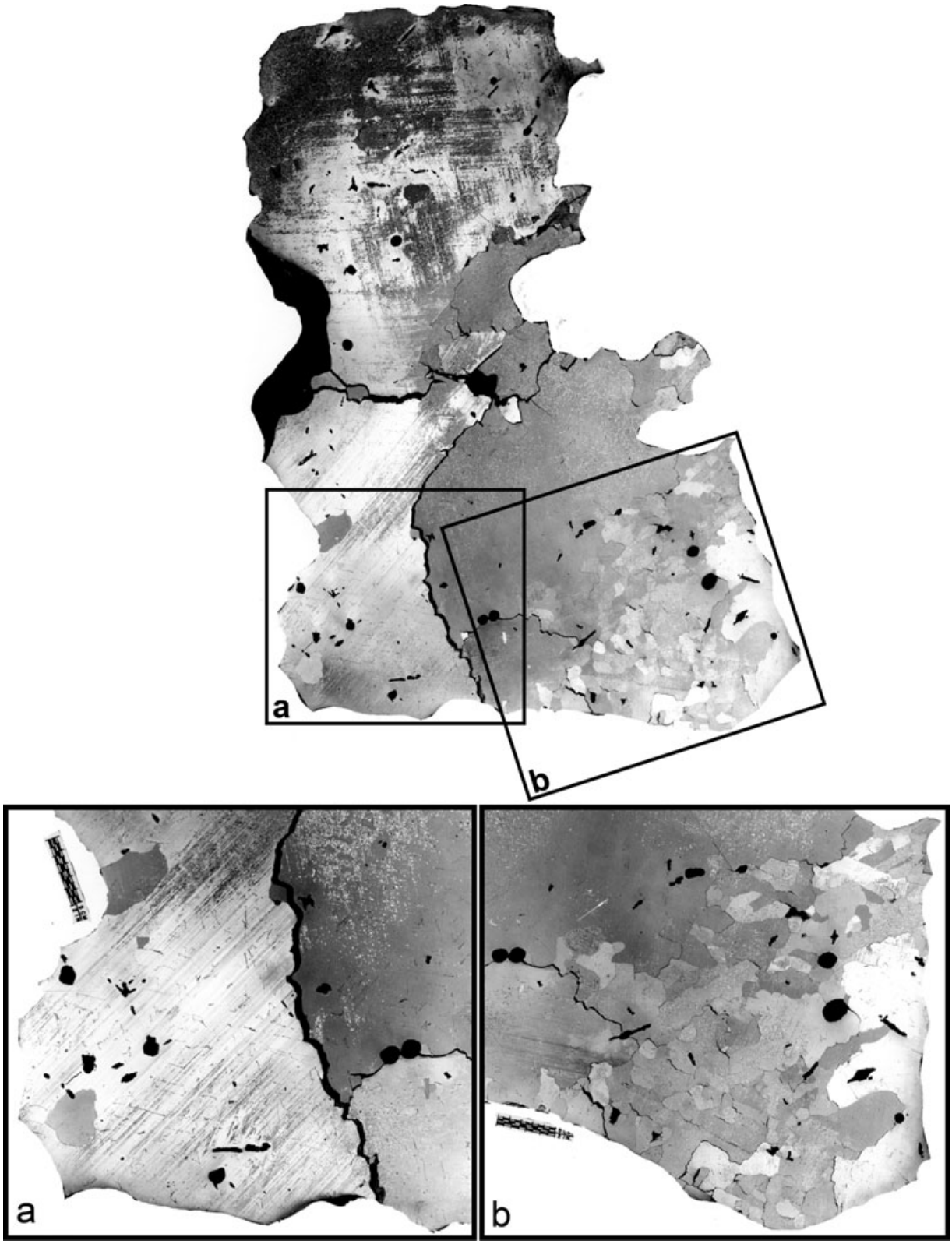

Fig. 9. Smithsonian photographs of the cut surface of the Old Woman meteorite. a) Enlargement of the hexahedrite region showing rounded to irregular sulfide inclusion (black), elongate schreibersite chains whose orientations are at 60°, and Neumann bands that cross cut the area. b) Enlargement of the octahedrite region emphasizing the coarse grained pattern. Photo credit: Victor Krantz (Smithsonian).

from less than 1 cm to more than 40 cm in maximum dimension, with a strongly bimodal distribution. Seven large grains comprise ~85% of the surface area and comprise the hexahedral structure within the meteorite (Fig. 9a), with the remaining 15% of the surface sampling the octahedral polycrystalline regions up to 20 cm in maximum dimension with grain sizes of 1–3 cm (Fig. 9b). More rarely, smaller grains are found completely enclosed (at least in two dimensions) within the larger grains. This bimodal distribution is not unknown, with the ungrouped iron New Baltimore exhibiting a mixture of equiaxial grains and Widmanstätten lamellae (Buchwald 1975).

Within the larger grains, kamacite is the only Fe,Ni metallic phase identified; extensive examination with scanning electron microscopy failed to identify taenite. If such a mass fell as an individual meteorite, it might properly be described as a hexahedrite, as indicated by Clarke (1979b). Below, we adopt this terminology and refer to these regions as hexahedral. However, these regions contain schreibersite chains that can reach several cm in length. Within these chains, individual schreibersites are 100–200 μm in width and can reach several mm in length. These schreibersites often exhibit embayments or skeletal morphologies. The chains occur in three distinct orientations at angles of ~60° and exhibit spacings of 0.5–1.5 cm, with an average spacing of ~1 cm (Fig. 9a). The schreibersites in these portions of Old Woman are similar to the ungrouped, low-Ni iron Zacatecas (1792) (Buchwald 1975), whose schreibersites exhibit similar morphology, orientations, and spacing. Also present within these large austenite regions are rounded, irregular, and elongate sulfide inclusions ranging up to 3 cm across (Fig. 9); elongated sulfide inclusions sometimes exhibit orientations parallel to those of the schreibersites. Mineralogically, the sulfide inclusions contain troilite and daubreelite, and are often rimmed by schreibersite. Throughout these large kamacite regions, small schreibersites (rhabdites) are common. Carbide and graphite are extremely rare, although we did find one schreibersite inclusion in a subsample of USNM 6358 near the edge of Old Woman rimmed by graphite and Fe metal which form distinct partitions perpendicular to the edge of the schreibersite. The morphology suggests that the graphite may have formed from decomposition of cohenite, a phenomenon also observed in the IIAB irons Cedartown and Keen Mountain (Buchwald 1975).

Small parent austenite crystals within the polycrystalline masses (Fig. 9b) are completely converted to kamacite and lack any internal structure, indicative of a remnant Widmanstätten pattern. These regions, if sampled as distinct meteorites, might be called coarsest octahedrites (Clarke 1979d). Again, we adopt this nomenclature and refer to these regions as coarsest octahedrite. At kamacite-kamacite grain boundaries, ribbons of schreibersite are observed, as are thin ribbons of sulfide. No taenite was observed in these areas. Sulfide nodules up to a few centimeters in maximum dimension are also observed within these regions. Traverses across schreibersite lamellae both in the hexahedral structure and at kamacite-kamacite grain boundaries in the octahedral structure yield essentially identical compositions of unzoned schreibersite of 21–22 wt% Ni and 14–15 wt% P with bordering kamacite exhibiting a pronounced Ni depletion. Rhabdites average ~35 wt% Ni. By comparison, large schreibersites in the IIAB hexahedrite Coahuila (bulk 5.6 wt% Ni, 0.3 wt% P) are slightly more Ni-rich (23.5 wt% Ni) and rhabdites are essentially identical in composition (35 wt% Ni) (Clarke and Goldstein 1978).

Overprinting the entire primary structure is extensive shock modification, including shock melting of troilite-daubreelite-schreibersite inclusions; Neumann banding, with each of the larger primary austenite crystals exhibiting 1–2 dominant orientations that cross the entire crystal; and formation of subgrain boundaries within kamacite on the scale of 200 μm to 1 mm, leading to an overall speckled appearance on the etched slice (Fig. 9). Similar shock features, particularly shock-melted sulfide inclusions, have been observed in a number of other IIAB irons (e.g., Hex River Mountains, Richland) (Buchwald 1975).

A heat-altered zone up to several mm in thickness was observed on sections of the meteorites and, in cracks or reentrants of the meteorite, we observed material, which appears to be a eutectic metal-phosphide melt that could represent material from the original fusion crust.

Chemically, Old Woman is a low-Ni, low-P member of group IIAB. Bulk chemical analyses of all three lithologies of the Old Woman meteorite by Jarosewich (personal communication) revealed an average composition of 5.86 wt% Ni (5.59 at%) (5.78–5.96 wt% range), 0.30 wt% P (0.56 at%) (0.29–0.31 wt% range), and 0.49 wt% Co (0.48–0.50 wt% range). Trace element analyses (Wasson and Willis 1976; Kracher et al. 1980; Wasson et al. 2007) reveal a composition intermediate in the range of IIAB irons. Kracher et al. (1980) suggested a compositional hiatus of 1 μg/g between IIA and IIB, placing Old Woman (0.80 μg/g) in group IIA. It is, however, generally accepted that a near continuous distribution of compositions exists and IIAB should be considered a single compositional group. We also note that Wasson et al. (2007) report a somewhat lower bulk Ni concentration (5.54 wt%) than Jarosewich (2006). In the absence of P data from Wasson et al. (2007) and considering the masses used for analyses by Jarosewich (7.5–12.7 g), it is possible that the aliquot measured by Wasson et al. (2007) was deficient in the relatively Ni-rich schreibersite common in Old Woman.

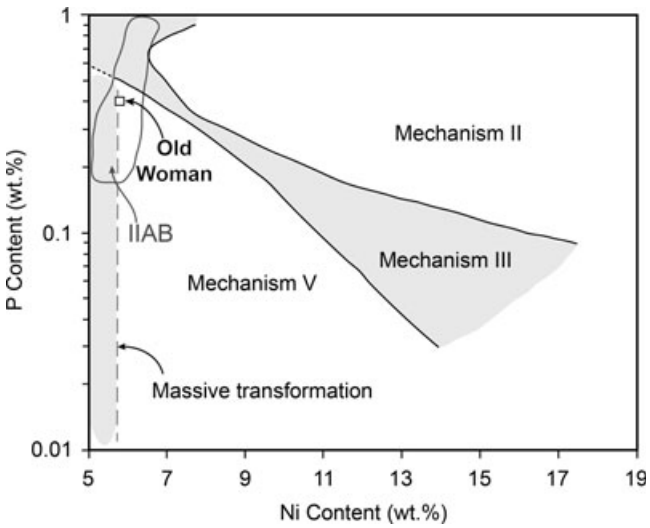

Fig. 10. Plot of Ni (wt%) versus P (wt%) illustrating the ranges of compositional space in which various mechanisms defined by Yang and Goldstein (2005) operated to form the Widmanstätten pattern. The range for IIAB irons and the composition of Old Woman (Jarosewich 2006) are shown. Old Woman lies near the intersection of compositions for massive transformation and mechanisms III and V.

The formation of the Widmanstätten structure in iron meteorites was reviewed by Yang and Goldstein (2005), who proposed three mechanisms for the formation of IIAB iron meteorites (Fig. 10). Hexahedrite members of group IIAB formed through massive transformation of taenite to kamacite, while the coarsest octahedrite members formed through either the pathway $\gamma \rightarrow \alpha_2 + \gamma \rightarrow \alpha + \gamma$ (their mechanism V) or the pathway $\gamma \rightarrow (\alpha + \gamma) \rightarrow \alpha + \gamma +$ ph (their mechanism III). The analyses of Jarosewich (2006) place Old Woman on the boundary between massive transformation and mechanism V and only slightly below the field for mechanism III in P. Given its complex structure and relative location in Ni-P compositional space relative to these various mechanisms, we examine how these mechanisms operated to form Old Woman and whether the same mechanism operated throughout the meteorite.

The first question to ask in examining the structure of Old Woman is why both hexahedral and coarsest octahedral structures evolved in the same mass. As noted earlier, this structure is not unprecedented, with New Baltimore exhibiting a similar bimodal distribution (Buchwald 1975). In the case of New Baltimore, Buchwald (1975) argued that it owed its unusual structure to nucleation of austenite crystals on sulfide inclusions, with higher nuclei densities leading to smaller grain sizes. In the case of Old Woman, such an explanation seems less plausible, given the multiple sulfide inclusions that are present in single hexahedral regions.

One possibility is that the coarsest octahedral regions could have evolved via the $\gamma \rightarrow \alpha_2 + \gamma \rightarrow \alpha + \gamma$ (mechanism V) or $\gamma \rightarrow (\alpha + \gamma) \rightarrow \alpha + \gamma +$ ph (mechanism III) pathways into their present polycrystalline state. The bulk composition of Old Woman would favor the $\gamma \rightarrow \alpha_2 + \gamma \rightarrow \alpha + \gamma$ pathway. As noted by Yang and Goldstein (2005), schreibersite may form at lower temperature if kamacite or taenite is saturated with P after the α phase forms. In the case of Old Woman, this would require complete conversion of γ to schreibersite. In this case, conversion of taenite to schreibersite occurred at kamacite-kamacite grain boundaries, producing the schreibersite ribbons now observed at these boundaries.

Although the bulk composition of Old Woman lies outside the compositional range for which the $\gamma \rightarrow (\alpha + \gamma) \rightarrow \alpha + \gamma +$ ph (mechanism III) pathway is favored by Yang and Goldstein (2005), the presence of abundant schreibersite in both the hexahedral and coarsest octahedral structures, and its apparent orientation mimicking that of the Widmanstätten pattern in the hexahedral portion, spur us to examine this possibility. The early stages of the $\gamma \rightarrow (\alpha + \gamma) \rightarrow \alpha + \gamma +$ ph $\rightarrow \alpha +$ ph pathway were described by Yang and Goldstein (2005). These authors noted that kamacite does not nucleate in the $\alpha + \gamma$ field, introducing the nomenclature $(\alpha + \gamma)$ to denote this fact. They did not consider the case of cooling to temperatures below that of the $\alpha + \gamma +$ phosphide field for mechanism III in low-Ni irons.

This pathway can be illustrated through six isothermal sections in the Fe-rich corner of the Fe-Ni-P phase diagram at temperatures of 850°C to 550°C (Fig. 11). By 750°C, the Old Woman composition has entered the two-phase $\alpha + \gamma$. By 550°C, it has entered the $\alpha +$ phosphide field. Between these temperatures, it is unclear whether Old Woman passed through the $\alpha + \gamma +$ ph field (which seems likely) or passed directly from $\alpha + \gamma$ to $\alpha +$ ph, as argued by Clarke and Goldstein (1978) for the Coahuila meteorite, which contains 5.29 atom% Ni and 0.51 atom% P. At 600°C, schreibersite contains ~13 wt% Ni, while phosphorus remains soluble in kamacite, which can incorporate 0.5 atom% P. The schreibersite continues modest growth in the $\alpha +$ phosphide field, reaching the measured Ni concentration of ~21–22 wt%. Much later, lower temperature nucleation produces the observed higher Ni concentrations, and small phosphide rhabdites.

It is not clear which, if either, of these pathways produced the coarsest octahedral structure in Old Woman. Additional detailed studies, such as transmission electron microscopy or electron backscattered diffraction, might elucidate the origin of this structure. It is possible, however, that neither of these mechanisms operated to

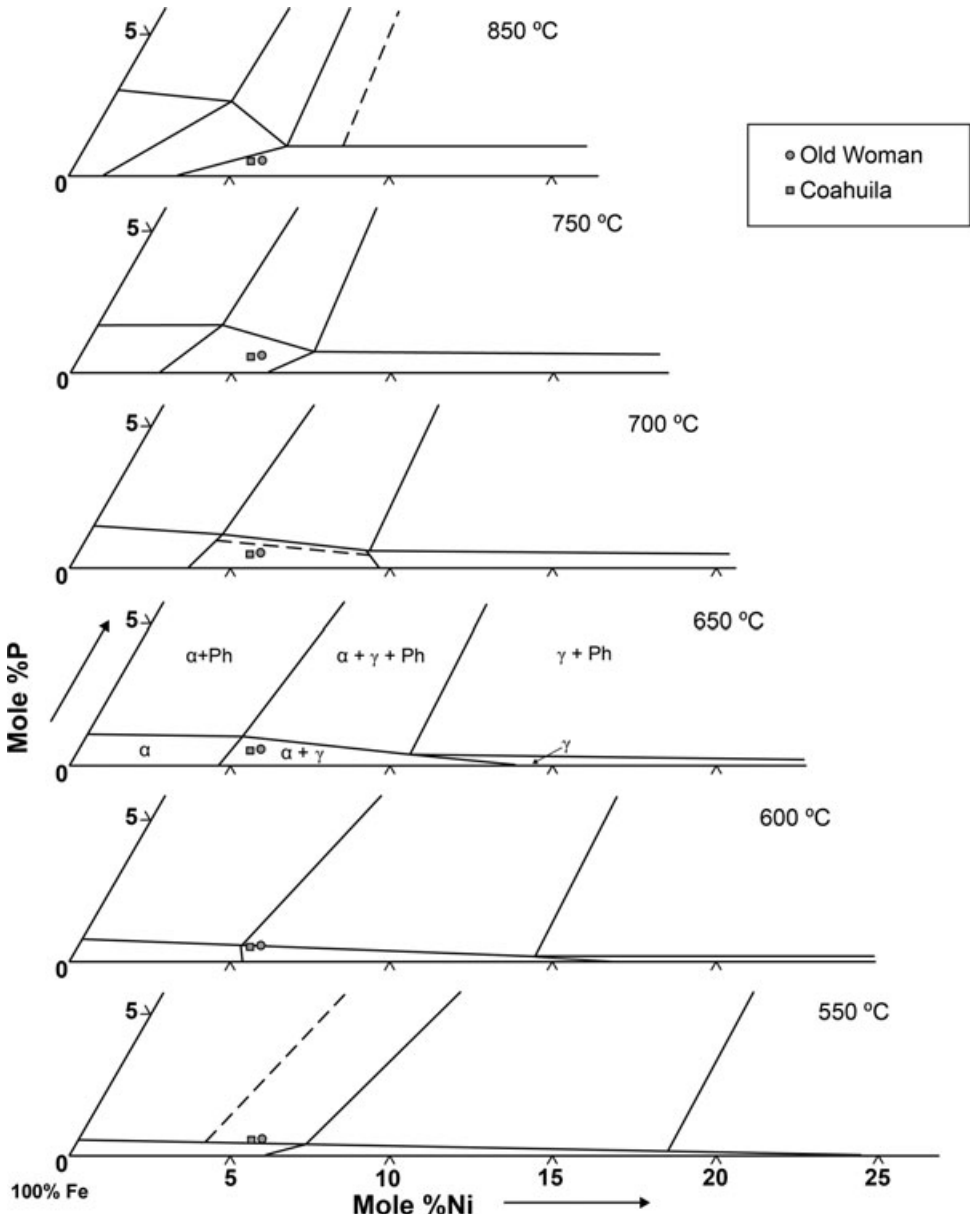

Fig. 11. Compositions of Old Woman and Coahuila plotted on isothermal sections between 850° and 550°C (Doan and Goldstein 1970) in the iron-rich corner of the Fe-Ni-P system. These compositionally similar meteorites evolve from γ (850°C) through α + γ (750°C to 650°C) to α + phosphide (550°C). Between 650°C and 550°C, it is unclear whether these compositions pass through α + γ + phosphide. It is possible that only the hexahedral portion of Old Woman passed through the three-phase field, while the octahedral portion passed from α + γ to α + phosphide.

form the hexahedral portion. At first glance, the $\gamma \rightarrow (\alpha + \gamma) \rightarrow \alpha + \gamma + \text{ph} \rightarrow \alpha + \text{ph}$ has the potential to produce both the kamacite-schreibersite associations observed in the hexahedral portion and elongated schreibersite chains oriented at ~60° suggestive of a remnant Widmanstätten pattern. This mechanism was suggested for the ungrouped, low-Ni iron Zacatecas (1792) (Buchwald 1975). However, later shock overprinting produced, among other features, Neumann bands within Old Woman. In the hexahedral portion of Old Woman, these Neumann bands appear to reach ~20 cm in length on the large slab and are observed microscopically to be continuous across the schreibersite chains. This suggests that the hexahedral portions are, indeed, single crystal kamacite. While complete conversion of γ to schreibersite could produce a kamacite-schreibersite assemblage, that kamacite would be polycrystalline. Diffusion rates and grain boundary migration would be too slow to allow coarsening to the hexahedral structure. A similar argument can be made

for Zacatecas (1792), where Buchwald (1975) illustrates continuous Neumann bands on either side of elongate chains of large, irregular schreibersites. Instead, the hexahedral portion may have formed via massive transformation ($\gamma \rightarrow \alpha_m$). At low-Ni compositions, this transformation occurs at relatively high temperatures. After this transformation, the large schreibersite chains formed and their irregular forms reflect this high-temperature formation.

Our preliminary examination of the metallography of Old Woman suggests that its diverse structure may owe to formation by one or more mechanisms within a single mass. This strongly suggests that further study of this fascinating meteorite, made possible by the large exposed surface produced during cutting of the main mass, may yield additional insights into the pathways by which iron meteorites in general transform during cooling.

CONCLUSIONS

Old Woman has the distinction of being the largest meteorite in the National Collection of Meteorites at more than 2.5 metric tons. Iron meteorites of this size, particularly those for which large slices exist, provide unique insights into the diversity and complexity that occur at the m-scale as a result of the crystallization and cooling of an asteroid core. If sampled separately, the individual lithologies of Old Woman might well have been classified as three distinct meteorites. Instead, we now recognize that transitional textural types do occur in close proximity, and can unravel the unique combinations of chemistry, nucleation, and cooling history that produce these textures.

It can be argued that the Smithsonian's long involvement with meteorites, its world-class collection, and its generous distribution of specimens to the national and international scientific communities present good reasons for continuing the policy of transferring meteorites found on federal lands to it for placement into the National Collection of Meteorites. There, they can be not only studied and disbursed effectively, but viewed by more persons than would be possible in any state museum (the National Museum of Natural History has more than seven million visitors a year).

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Editorial Handling—Dr. Christian Koeberl

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article:

Fig. S1. Pencil sketches of a study of the Old Woman meteorite, drawn for the Smithsonian by artist Marcy Dunn Ramsey (marcydunnramsey.com), based on photographs and a study of the meteorite. The triangular legend shows the direction (labeled) from which each view was drawn, with View D drawn from the bottom of the meteorite (view opposite to that seen in the legend drawing). The maximum dimension of the meteorite in these images is in the range of 0.8 to 1.0 m.

Fig. S2. These images are pencil sketches of the find site of the Old Woman meteorite, a boulder field on a slope in the Old Woman Mountains of California. Drawings by Marcy Dunn Ramsey (marcydunnramsey.com) based on photos of the find site and study of the meteorite for the Smithsonian Institution. The deeply pitted iron meteorite is approximately 1 m across in these perspectives.