Magnetic survey to locate Manila galleon
Baja California, Mexico
Dr. Sheldon Breiner

Evidence of the visit and possible demise of a Spanish galleon has been discovered in the sands of a beach in Mexico. Numerous artifacts indicative of a nearby Spanish galleon were found amongst 3-meter to 15-meter high sand dunes in the desert terrain. Such evidence, of course, indicates the probable presence of a galleon offshore. One of the means of detecting its actual location, then, is to map material from the galleon itself, its cargo or personal effects of the crew. Among the detectable items would be ferromagnetic artifacts, be it cannon, anchors or spikes in the hull or small miscellaneous iron artifacts, all of which are detectable using a sensitive magnetometer.

The visible line of porcelain shards, beeswax, lead sheets and other such material form a linear dispersion pattern almost 5 km long parallel to the shoreline, but 400 meters inland. One end of this pattern, (call it the 'head' of the line and closest to its source) is a hundred meters wide, the other, twice that. It has been surmised that this line represents the old shoreline at the time of the sinking of the galleon.

The Setting

This background setting of this site is a result of offshore eddy currents; strong daily unidirectional winds from the solar-heated desert terrain and its nearby high mountains; offshore source rocks producing an inexhaustible supply of sand; and the nature of the nearby bay that creates wide littoral conditions that produce a shallow flat sea-bottom, several hundred meters wide near shore. The latter is the most likely site of the galleon.

By Gordon Miller, with advice of Ray Aker

In this analysis, we will demonstrate that, with the thorough understanding of these conditions, the disposition of the artifacts and knowledge of 16th century ships, it might be possible to derive the conditions for the location, but not its demise, of one such ship, the *San Felipe*, in the year 1576. Moreover, it will be demonstrated that it might also be possible to determine the exact *location* of the hull offshore by conducting magnetic surveys.

Reconstructing the possible events of that day long ago, the ship, or parts of it, may have remained there for perhaps tens of years, certainly long after the crew had perished. The boat careened, leaning towards shore, with the ballast stones and heavy cargo forcing the main part of the hull into the sandy bottom, where it finally became entrenched. However, sea swells every minute or so caused the hull to flex, part of breaking off, carrying some artifacts onto the shore and over time dispersing it along the beach. A report of a local priest 175 years later noted the presence of part of hull containing the same suite of artifacts scattered in the dunes discovered 430 years after the sinking of this boat

Once on shore, the porcelains would be scattered along the high water line, moving down-shore, down-wind at each storm or high water surge. A few pieces of lead sheets (used to protect the hull), 30 kg pieces of beeswax and some unbroken porcelain, found near the head of the line of shards, indicates that heavy or delicate artifacts must have been in a protective environment when washed ashore, whereas smaller pieces were

carried along by storm wash downwind downwash along then beach. When the advancing, accreting shoreline moved seaward far enough (one meter/year) to effectively place the porcelain shards and other items in a protected inland domain ("effectively place," even though the porcelain did not, itself, move) amongst and between the dunes..

The vast majority of the heavier cargo such as the rest of the porcelain, wax-dipped silk if it survived, other items, as well as the ballast stones, anchors, cannon (if any), lead sheet lining the outside of the hull, iron pins holding the keel to the ribs, etc., would remain with the lower hardwood hull, under the sea bottom.

Many 20 to 30 centimeter-long water-eroded, rounded, igneous boulders, were also found near the head of this line, some magnetic (as is common for igneous rocks) though many were also found at other points. The wide distribution of these boulders may rule out these as ballast stones.

Inasmuch as the search involves the use of magnetometers to conduct surveys, it is important to reconstruct the possible events which occurred in 1576 and afterwards to shed light on where and how to conduct surveys. Magnetic detection of surviving iron objects is not diminished (except for distance to the magnetic objects) by the presence of the sand and silt over the site, nor does the condition of the dense teak and mahogany hardwood hull, its ballast, anchors and other material affect detecting iron objects that might have survived the centuries in this protected, anerobic (no oxygen) environment.

Thus, taking all of this into account, the ship, with its 5 meter draft, would have run aground at approximately the 5 meter depth in 1576. Today, however, the 5 meter depth is only 3.3 meters due to the seawards shift 400 meters during the past 430 years. The whole bottom profile - the shoreline, bottom contours and their associated depth -- shifted seawards horizontally by this amount.

These ships typically had large constituent parts or ancillary equipment that were comprised of either iron or rocks that might be detectable by *magnetic* means. A sensitive magnetometer of the type available for this survey can detect the very subtle effects of magnetic objects through sand, silt, water-- practically anything - and can be towed behind a boat, if the site allows, on a systematic survey to cover a large area.

Among the items carried by such ships of that vintage were iron cannon, anchors, ballast stones of possible igneous or volcanic rock, large pins used to hold together major wooden members, utilitarian objects, personal effects of the crew of 200 persons, small weapons, utensils, and other small iron objects and cargo. But for this

Pacific area and the time, iron cannon were not likely to be present, for in the 16th Century ships sailing in Pacific waters did not use iron cannon.

The search area is defined by a forensic-style analysis of the artifacts indicating that the galleon would indeed be just offshore this area. The water depth is very shallow in the target area of search. This condition is both good and bad: the objects are closer to the magnetometer sensor making them more detectable; however, the shallow water and accompanying surf/sea conditions and variable bottom topography with tides and terrain made it impossible to conduct a systematic survey and required, instead an 'opportunistic' survey mode. In some areas we used a portable magnetometer with the magnetometer sensor affixed to the prow of a local fisherman's panga, an eight meter-long fiberglass (therefore non-magnetic and non-interfering) boat. In deeper water, we towed a magnetometer sensor in the water.

<u>Equipment & Operations</u>
The key instrument for this work was a Geometrics G-882 marine cesium magnetometer. The magnetometer is comprised of a sensor, housed in what is called a 'fish', towed behind the boat. Keeping the sensor away from the boat isolates the magnetic items on the boat, such as the engine, our equipment and the electric current from the batteries, from affecting the highly precise measurements of the magnetometer. This instrument, while under tow, can resolve a local change of about 0.05 nanoTesla, abbreviated nT. As a practical matter, however, one can recognize a local anomaly as small as 0.1 nT which is almost one millionth of the earth’s magnetic field. (0.1 nanoTesla = 0.1 gamma, or 10^{-6} gauss = 10^{-6} oersteds) The earth's magnetic field ranges from about 30,000 nT to about 60,000 nT. The magnetometer specifications can be found at ftp://geom.geometrics.com/pub/mag/DataSheets/882ds.pdf

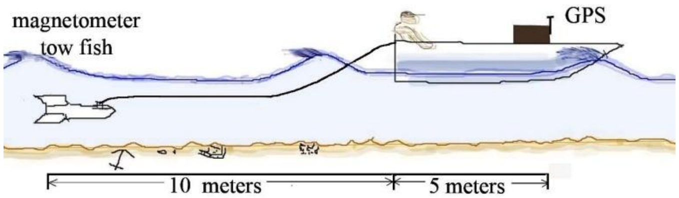
The fish is equipped with a transducer to transmit its depth-of-sensor below the surface. At our tow speed, estimated to be approximately 3 meters per second (about 5.8 knots), the sensor was typically 1.5 meters below the surface in water about 4 meters deep, placing the sensor about 2.5 meters above the bottom.

Location information is transmitted via a serial cable from a GPS unit mounted 5 meters in front of the stern on a PVC pipe about 1.5 meters above the boat. It locked on to as many as 12 satellites (horizon visible in almost all directions).

A PC laptop computer, is used to control all functions of the magnetometer. The computer is used to control, display and record all data, including, magnetic intensity (displayed in analog form), GPS locations, depth of sensor below the surface, depth of sensor above the bottom, time/date and sensor signal level.

The fish was towed 10 meters behind the stern of the boat. The magnetometer cable was fastened to the boat via strain relief nylon rope tied to one of the fiberglass fillet corner braces at the stern. An extra, emergency attachment to the tow cable was made by tying the cable, at a point tens of meters up the cable, to another point on the boat, to prevent all the equipment, PC and all, from being dragged out of the boat, should the fish get snagged, on, say, some unseen wreckage or rocks.

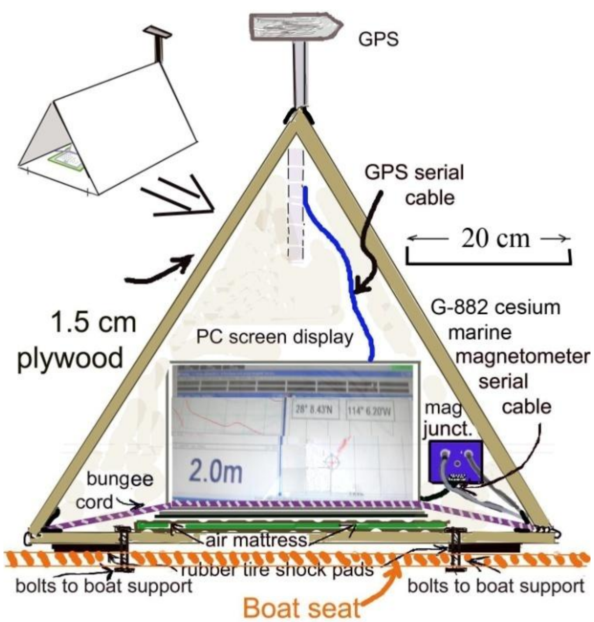
A correction was made in the data logging to account for the 15 meter distance between the magnetic sensor and the GPS because the actual real-time sensing of an anomaly would otherwise have lagged the apparent location by that amount. In other words, the GPS location in the boat, in real time, actually precedes, in time, the magnetometer passing over an anomaly by a distance of 5 meters ahead of the stern plus 10 meters tow distance to the rear of the boat..



Magnetometer, panga tow configuration

It was important to protect the equipment such as a delicate laptop computer and electrical connections from the severe pounding where the tiny panga would sail off into space from the peak of a swell landing hard in its trough, or be hit by a large wave breaking over the bow. The screen of the laptop, including visibility of the cursor, was command central and had to be observed at all times in the presence of direct sunlight. Providing dry-finger access to the touchpad and keyboard of the computer was yet another challenge.

A protective housing was constructed at the site using plywood in an A-frame structure, nicknamed the "dog-house". This protected the computer, provided a platform for the GPS system, computer access, maintained dry electrical connections and shielded the batteries from damage. Cables necessary to come into the dog-house were passed through for magnetometer power, magnetometer signal, magnetometer sensor, AC power for laptop, GPS serial, and magnetometer junction box. The dog-house was bolted down to the boat frame and insulated for high-freq shock by tire rubber at four points, while the computer was insulated for severe shock and microphonics by a partially-deflated air mattress, with the laptop held down against the air mattress and A-frame by a bungee cord.

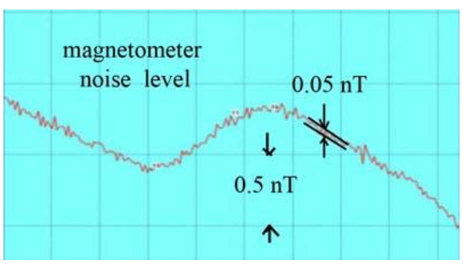


With this understanding of the challenging objectives, it is important in this report to present the critical basis for understanding how we can squeeze out the detection, mapping and understanding of incredibly small, but significant magnetic anomalies, some smaller than may have ever been seen at sea (or even on land). This site is at once both clean magnetically speaking and magnetically difficult due to a diverse set of disturbing sources of magnetic noise. It is clean compared to most land-based magnetic survey sites due to the rarity of persons over many years dropping magnetic debris. The sand is uniform with little man-made iron detritus (basura), organically-generated magnetic anomalies or near-surface magnetic rocks.

As will be shown, this site presents a rare and useful opportunity to actually see and characterize possible artifacts that would never be noticed in a normal, standard-resolution magnetic survey. This is true provided the magnetic anomalies are sufficiently understood to discriminate meaningful sources from virtual or background magnetic anomalies from such diverse sources as effects of the sun, deep-seated geologic bodies, electrical currents from the motion of the swells in the earth's magnetic field, differentiating old iron from modern steel, effects from the boat, noise level of the magnetometer, appearance of anomalies due to distance to the side or beneath the sensor and the background regional magnetic gradient of the earth. In most of these cases, these sources of noise were minimal.

Observed Magnetic Anomalies

While under tow, one can notice noise due to the magnetic effects of sea swells. Salt water is electrically conductive and when it moves through the earth's magnetic field generates an electric current and its associated magnetic field—by the same principle by which a generator produces electricity.. This effect is proportional to the speed, height and direction (with respect to the earth's magnetic field) of the sea swells and the total mass of water moving (most of which is beneath the surface). These effects were about 1 to 3 nT under some of the larger swells experienced this time while under survey. And, for surveying at the surface of the ocean, this effect limits the eventual resolution.



Basic electronic noise level of the magnetometer while being towed is about 0.05 nT.

Sometimes, in archaeological sites, the presence of an object disturbs the local flow of water, in particular, magnetite-bearing water and sand. This causes the water to slow down depositing magnetite around such objects causing small magnetic anomalies detectable with a sensitive magnetometer. Magnetite has a specific gravity of 5, making it rather heavy compared to sand grains and rock particles..

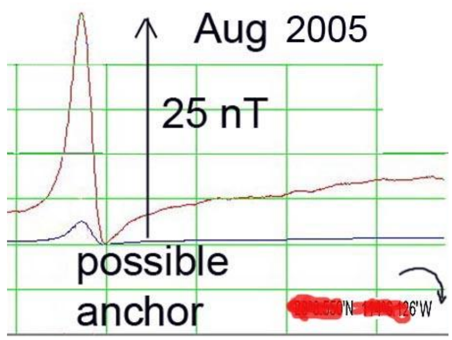
In the interpretation below of some of the small, but perhaps most significant anomalies, this background is removed by subtracting, point-for-point, the values of this straight-line background slope from the actual observed profile to examine the "pimple on the sloping elephant's back." As will be noted again below, the large anomalies are usually not the most important. We are not searching primarily magnetic objects, but rather using the magnetic properties to find things that are made of other, non-magnetic material.

If one is interested in learning how to interpret such magnetic data, understanding magnetic anomalies and the nature of the earth's magnetic field as it affects what is being observed in this survey, see, "*Applications Manual for Portable Magnetometers,*" or, the AMPM, which can be downloaded at this site http://tinyurl.com/ManualMagnetometers

The result of these reconnaissance profiles, sampling as it were, of the target area, was that we acquired some interesting data, none of which thus far is indicative of a modern (late 19th or 20th century) ship. Reconnaissance survey tracks covered a much larger area without noting anomalies, other than a modern wreck of a small boat 3.5 kilometers south of this site.

Interpretation

Several magnetic surveys were carried out in the ocean over the past decade or so. Some surveys conducted in shallow waters (<3 meters) utilized portable magnetometers on the survey boat, some, in deeper waters (>3 meters) using marine towed magnetometers. In general, a few larger magnetic anomalies were located that appeared to be likely caused by anchors, most noted in the deeper waters. See examples below.



Similar anchor anomalies were observed either isolated as above or in among other anomalies in groups, termed here as ‘clusters.’

Closer to shore, about two hundred meters from the shore there appears that we have two principal clusters of anomalies, the most likely indicator of the galleon's location, each about 15 meters wide. The North Cluster is about 65 meters north-east of the South Cluster, both in the flat-lying surf-zone with a few outlying anomalies not far from these.
Included among these were a couple of anchor anomalies. See view below of this quiet surf zone.

An anomaly 35 meters northwest of the North Cluster appears to be an anchor. There is also an anchor in the center of the North Cluster. The South Cluster exhibits many smaller objects whose average mass is about one-tenth to one-twentieth the magnetic moment (magnetic 'mass') of the presumed anchors. One small completely non-magnetic mass in the North Cluster

could be a large mass of wood (as the bulk of the hull, or cargo, such as porcelain). [If curious about how a magnetometer can detect something that is not, in itself magnetic, please read on.]
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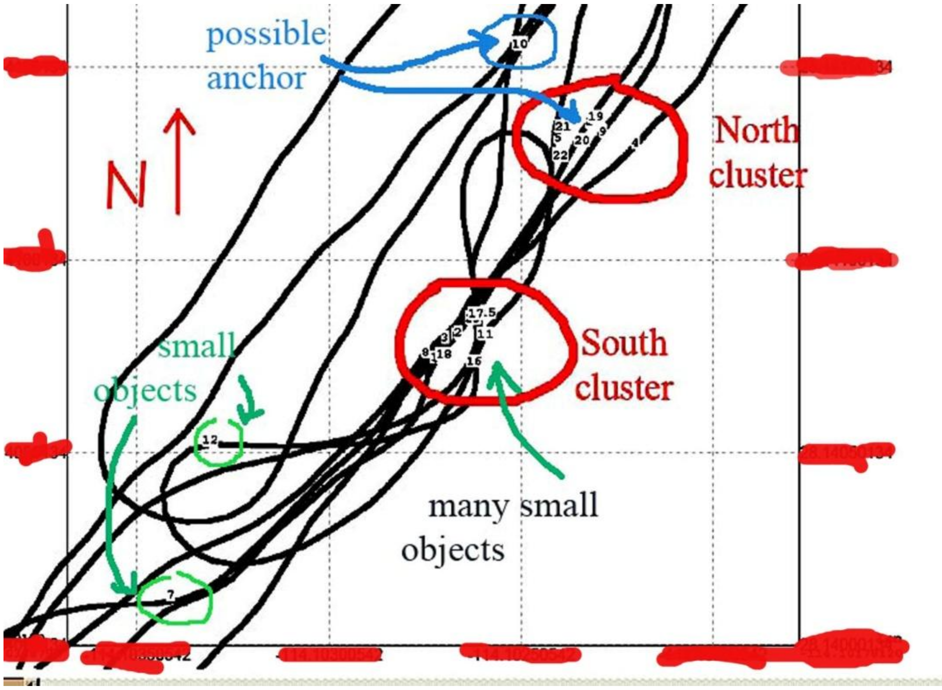
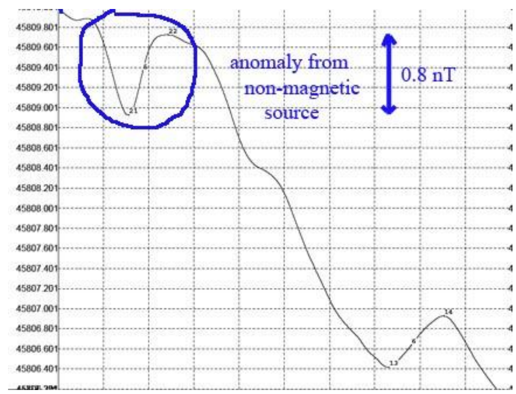


Tracks of profiles conducted in one part of survey area. Small numbers are magnetic anomalies

All of the larger anomalies are caused by single iron-containing objects, almost certainly, anchors, perhaps six or so in total. The basis for this interpretation is that they are singular *induced* anomalies with no significant *permanent* magnetism (a characteristic of modern steel) component, because their highs and lows are consistent with the classic induced character of such a dipole-induced source. They are not compound anomalies but rather individual, distinct anomalies.(a pile of iron objects would look very different with bumps on the curves, broad and broadly complex. A steel object, say, from a modern manufactured source, commonly has more than one manufactured part and one with a high degree of permanent magnetism and would most likely exhibit "distorted" shape anomalies with exaggerated highs or lows, even reversed positions of the highs and lows with respect to magnetic north or south. See examples in diagram.

[presence of high permanent magnetism makes the anomaly's signature, owing to the magnetic north and south poles, determined by the orientation of the object, more than its shape, so that its characteristic pattern when measured by a total-field-measuring magnetometer such as this cesium magnetometer produce an anomaly where the high and low associated with the anomaly does not follow the classic, high-on-south, low-on-the-north 2D signature, at this magnetic latitude. A piece of iron, without the magnetic, or, for that matter, physical, hardness, would exhibit only induced magnetic effects and, almost regardless of shape, would produce a simple, predicted signature as seen in plan view. In some ways, an ancient wreck with only simple iron objects presents a much simpler magnetic pattern of debris compared to a modern ship or junkyard where various kinds of ordinary steel and other such iron alloys presents very complex shapes and sizes and where the size of the object sometimes bears little relationship to the amplitude and shape of its magnetic signature. See Chapter VII of the AMPM cited earlier]

Within the limitations of having only a few scattered profiles, the ‘anchor’ anomalies are from single iron objects, perhaps anchors or iron pins very close to the sensor comprised of about 5 kilograms of iron (effective, reflecting loss of original iron mass). An anchor of 20 kilograms original weight might have lost 50 to 75% of its ferromagnetic mass over the years. (the iron oxide product, that is, rust, is not ferromagnetic.) The observation that both are of comparable amplitude would indicate they are two of the same kind of object, e.g., anchors, pins or such. Miscellaneous small magnetic anomalies, less than 1 nT in amplitude, could be different kinds of objects or ballast stones of volcanic or igneous rocks (high density, good for ballast).



Owing to the high magnetite content of the source rocks from the metavolcanic rocks further offshore, the sand has a high average content of magnetite. The sensor passing over a uniform magnetite-rich sand does not exhibit any anomalies. However, if sufficient sand is displaced by a non-magnetic mass, say, ship's timbers or cargo mass, there would be a void in the magnetic background manifesting itself as a negative anomaly, though very small compared to the large anomaly of a ferromagnetic source due to an anchor or iron pin. The anomaly shown here could be caused by major pieces of the hull, keel and ribs, or perhaps a mass of cargo material which by itself is not magnetic, but displace something which is magnetic. It is only contrasts in magnetization that are measured by the magnetometer. To recognize and interpret an anomaly with an amplitude of only 0.8 nT requires an ideal set of circumstances, such as we have here at this site.

Based upon an interpretation of the magnetic signatures, it is possible to construct the following scenario of that time period in the few years beginning about 1576: The ship, and/or its crew, was presumably in some kind of difficulty and decided to enter the local bay. Owing to the surprisingly shallow bay, it began catching bottom and, to save itself from drifting further into shore and the certainty of being grounded, set anchor 35 meters NW of the North Cluster. Some time later, crew on board or not, the ship broke loose from that anchor and became grounded and careened at the location of the North Cluster, in about 5 meters of water, a depth just less than the draft of a 400 ton galleon. After some time, perhaps a few years later when the ship had lost its integrity, possibly because of a major storm, it experienced a partial breakup. Some of the cargo spilled out and it lost another anchor. Some of the detritus, including both ferromagnetic objects as well as magnetically non-detectable material, represents the core of the North Cluster.

Some time later, the ship or major parts of it, now somewhat lighter and, driven by both winds and currents, floats downwind, a bit closer to shore. It may have been a major storm or just the prevailing winds then as today. The ship ran aground again after a distance of 65 meters, at the location of the South Cluster. The principal remains of the hull, remaining cargo and other contents comes to its penultimate resting place at the South Cluster. Any parts of the galleon remaining at the North or South Clusters that protruded above the bottom sands, will have been eroded by both physical ablation by the current-driven sand and silt as well as by chemical erosion and will not be seen today.

At the South Cluster, a major section of the hull, suffering the final ignominious demise from a major storm, sheared off carrying with it some of the galleon's contents. This piece of hull and contents were carried and deposited on shore, representing what has been found by our crew.

The most convincing evidence that the Clusters are manifestations of what is left of the hull and the associated cargo is that on the beach, in line with the Clusters, is a 15 meter wide path under which several significant objects have been discovered. Among these objects are the ‘ship’s compass’ and some silver coins. It appears that this linear zone might exist for perhaps one or two hundred meters inland.

<u>Conclusion</u>

There is sufficient magnetic data to utilize the information to guide the next steps in confirming, precisely, the presence of the galleon. The water depth is only about 2 or 3 meters at the 'putative' galleon location in the North and South Clusters. The maximum tide at certain times of the year is about 1.5 meters. The North Cluster is several hundred meters from the high-water mark. Therefore, it is possible to walk to the North Cluster and be only waist-deep in the water. Equipped with a portable magnetometer to confirm one is standing over many small local anomalies in the North Cluster, the bottom can be pierced using non-magnetic rods to probe for the presence of the hull at both the North and South Clusters. Once confirmed, a heavy, rock-based buoy will be planted to mark those points for confirmatory follow-up and excavation. [It appears that the recovery plan is to bring up the boat, place it on a truck for transportation to a laboratory in Ensenada.]

Present on the panga were Jack Hunter (formerly, California State Archaeologist with CalTrans in San Luis,Obispo, California); Roberto Galindo (formerly, magnetics specialist and diver with the Nautical subsection of the Instituto National de Historia y Archaeologia [INAH] from Mexico City), Sheldon Breiner (geophysicist and specialist in the application of magnetometers for search and exploration from Palo Alto, California). Appreciation is expressed to Geometrics of San Jose, CA for loan of the cesium magnetometers.