Identifying oil-field salinity sources with airborne and ground-based geophysics: A West Texas example

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Salinization of soil and groundwater resources is a common problem in the central and southwestern United States where infiltration of saline water into the shallow subsurface impacts wildlife habitat, restricts or eliminates agricultural uses of land, and pollutes aquifers and surface water bodies. Public concern about the environmental effects of saline water has increased interest in identifying salinity sources and determining whether oil-field brine has been introduced into the subsurface, where it has migrated, and whether it is the cause of specific problems on the land surface, in water wells, and in surface water bodies.

Major potential causes of salinization include (1) natural discharge of subsurface brines through permeable units, fractures, or joints; (2) upward movement of brine across confining beds through oil and gas wells, and deep, unplugged water wells; (3) infiltration of produced brine beneath surface pits; and (4) evaporative concentration of groundwater from shallow water tables that have risen in response to agricultural landscaping and consequent increased groundwater recharge (Figure 1). Although increased salinity from any of the natural, oil-field, or agricultural sources increases the electrical conductivity of the ground, each source may have a unique geophysical signature. For example, ground conductivity that decreases downward may indicate a surface salinity source such as a brine pit or evaporative concentration. Conductivities that increase downward may indicate deeper salinity sources, such as a natural flow path. Areal conductivity patterns and magnetic data from airborne surveys might help further distinguish oil-field sources (point sources with magnetic anomalies) from other sources (curvilinear features without magnetic anomalies).

In this study, we evaluate the use of airborne and ground-based geophysical methods to locate near-surface saline water and discern its source in a test area where salinization arises from natural sources, oil-field activities, and agricultural practices. An airborne electromagnetic and magnetometer survey of a 91 km^2 study area near Hatchel in Runnels County, Texas, defined the geophysical signature of salinized areas that have an oil-field source. The electromagnetic survey was designed to locate conductive ground associated with the presence of saline water. The magnetometer survey was designed to locate magnetic anomalies caused by well casings. Airborne geophysical signatures that might indicate a leaking well included conductivity anomalies at one or more of the electromagnetic exploration depths and either an associated magnetic anomaly or a known well location. Ground investigations focused on sites identified from the airborne survey. These included detailed geophysical surveys of sites and chemical analysis of soil and water samples. Because ground conductivity is not simply a function of pore fluid chemistry but is also affected by soil type, rock type, and moisture content, these factors were considered. We then interpreted the most likely cause of the conductivity anomaly.

Oil and gas wells provide potential paths for brine to move to the near-surface environment. Oil and gas fields cover much of the Hatchel quadrangle. Railroad Commission of Texas records indicate at least 700 wells are in the study area and that most drilling and production oc- curred before the 1969 order banning surface pits. Where brine is produced with oil or gas, as it is in the Hatchel area, produced brine was often pumped into surface pits and left to evaporate or infiltrate the ground. Pressurized brine within nonproducing geologic units, can also reach the near surface through deep water wells and

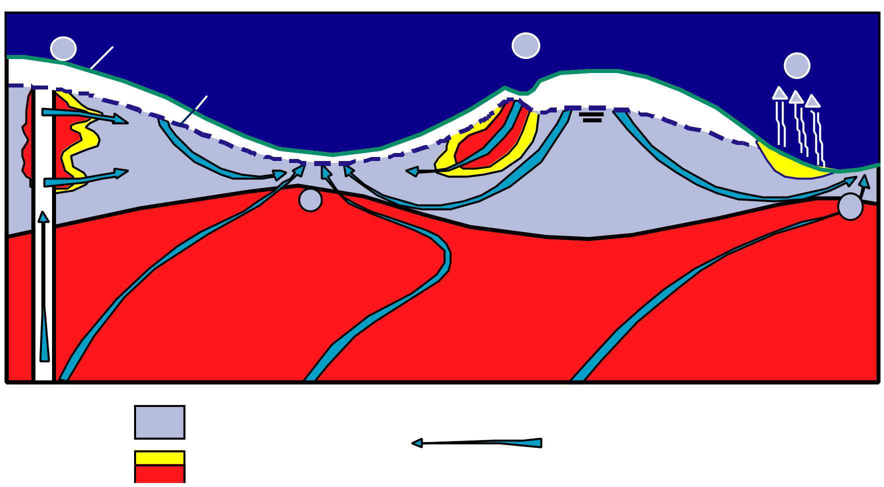

Figure 1. Conceptual model of salinity sources. Potential sources are (1) natural discharge of brine through permeable stratigraphic units, fractures and joints; (2) upward flow of brine through inadequately plugged and leaky boreholes; (3) infiltration of saline water beneath brine disposal pits; and (4) evaporative concentration of shallow groundwater.

improperly plugged oil and gas wells.

Methods. Electromagnetic induction methods were used to measure apparent ground conductivity using airborne and ground-based instruments. The tools are analogous to those used in borehole induction logging. Electromagnetic induction methods employ a changing primary magnetic field created around a transmitter coil to induce a current to flow in the ground, which in turn creates a secondary magnetic field that is sensed by the receiver coil. In general, the strength of the secondary field is proportional to the ground conductivity. One assumption is that the near-surface environment consists of horizontal layers of infinite lateral extent. Although this is untrue in the Hatchel area and in most oil fields, near-surface layers generally have sufficient lateral extent to render this assumption valid at the measurement scale.

Airborne magnetometer surveys have been employed in South Texas to locate well casings by mapping small magnetic-field perturbations. Combined airborne electromagnetic and magnetometer surveys have been completed recently in Mississippi to locate conductivity and magnetic anomalies associated with brine-leaking wells. In our survey, a similar high resolution airborne electromagnetic and magnetometer survey was flown at 100-m line spacing and 3-m sample spacing by Dighem. Flight heights were 30 m for the electromagnetic induction coils and 40 m for the magnetometer. Results included maps of ground conductivity at three frequencies (56 000 Hz, 7200 Hz, and 900 Hz), magnetic field maps, and conductivity cross-sections. The maps, locations of known oil and gas wells, and soil and geology maps were imported into a geographic information system (GIS) and analyzed to identify sites having a geophysical signature that might indicate an oil-field salinity source.

We conducted detailed on-the-ground geophysical investigations at sites that are representative of the anomaly types observed in the airborne data. Ground investigations included magnetometer surveys to locate wells, conductivity profiles to establish the relationship between the conductivity anomaly and the well, multiple-coil-separation electromagnetic surveys to establish the lateral and vertical extent of highly conductive ground, and time-domain electromagnetic (TDEM) soundings to determine the geometry of the saltwater plume.

Hatchel airborne results. Magnetic field data acquired during the airborne survey show abundant local magnetic anomalies superimposed on a regional gradient (Figure 2). Magnetic field strength increases along the regional gradient from southwest to northeast. Linear and oval magnetic anomalies are superimposed on the regional gradient. The anomalies are weak relative to the total field strength (as much as 30 nT), but are well above the 0.01-nT magnetometer sensitivity.

Most anomalies are 80-200 m across in an east-west direction (along the flight lines), where magnetometer measurements were acquired at 3-m intervals. Many, coinciding with known well locations, are interpreted to be local perturbations caused by ferrous elements of the well (casing and pump jack). Alignments of small anomalies on adjacent flight lines reveal some pipeline locations. Other magnetic anomalies coincide with structures containing significant ferrous material, such as some homes, metal barns, and windmills. The presence of oil and gas wells in areas where no magnetic anomalies are mapped confirms that not all wells were detected at the 100-m line spacing.

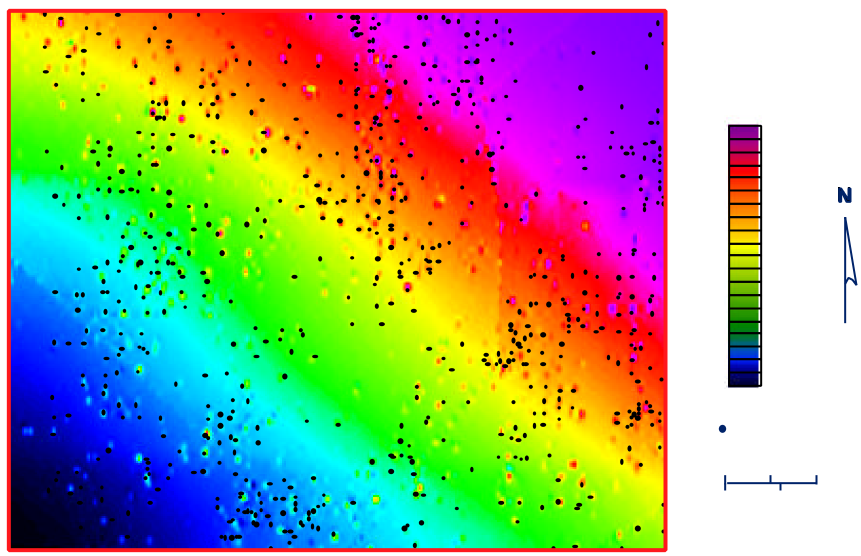

Figure 2. Map of total magnetic field strength. Superimposed on the southwest-northeast regional gradient are small anomalies that correlate well with known oil and gas well locations (black circles). Well locations provided by the Texas Railroad Commission.

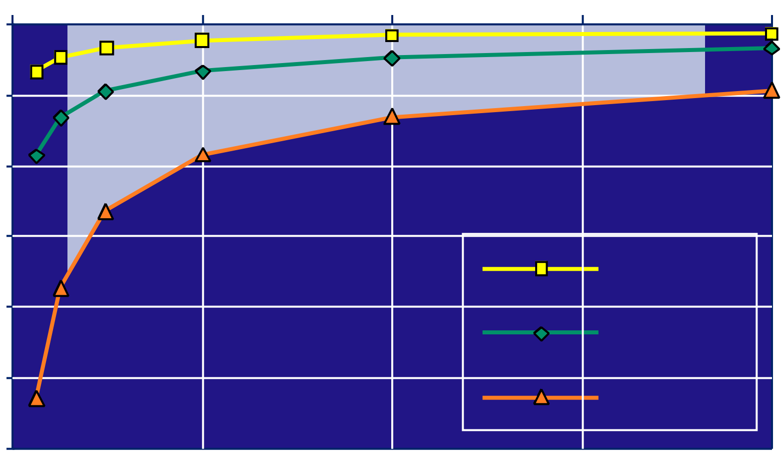

Figure 3. Changes in estimated exploration depth (skin depth) with ground conductivity for 900 Hz, 7200 Hz, and 56 000 Hz coil configurations. Gray area indicates conductivity range observed in the Hatchel area.

Ground conductivity maps of the study area were produced from airborne data obtained by horizontal coplanar coils operating at 56 000 Hz, 7200 Hz, and 900 Hz. Because exploration depth depends on both frequency and ground conductivity, deeper exploration depths were attained at lower coil frequencies and, for a given coil frequency, less conductive ground (Figure 3). Ground conductivities measured by the 56 000-Hz coils, the shallowest exploration depth frequency, were 60-730 mS/m (Figure 4). Exploration depths for this frequency deepen from 3 m over highly conductive ground to 9 m over ground with the lowest conductivities. This depth range is the one most affected by near-surface changes in factors that control ground conductivity, such as soil type (clay soils are more conductive than sandy soils), moisture content (wet soils are more conductive than dry soils), and water chemistry (saline water is more conductive than fresh water). Highly conductive areas visible on the 56 000 Hz map include numerous ovals generally 80-250 m across, curvilinear features that are tens to a few hundred meters wide and hundreds of meters long, and large irregular features covering many square kilometers.

A map of ground conductivity, as sensed by the 7200 Hz airborne coils, shows a conductivity range similar to that observed at the higher frequencies. Exploration depths are more than 20 m for the least conductive ground to about 7 m for the most conductive. The 7200 Hz map contains less highly conductive area than the 56 000 Hz map, which suggests that many conductivity anomalies on the latter represent shallow features. There are fewer local anomalies on the 7200 Hz map than on the higher frequency map.

Highly conductive ground, as measured by the 900 Hz airborne coils, covers even less total area. The conductivity range is also lower; most measurements are 60-400 mS/m. Maximum exploration depths are about 70 m for the least conductive ground and about 25 m for the most conductive. The principal feature is a 4- to 5-km band of highly conductive ground that trends north-northeast. The north-northeasterly trend of the conductive band coincides with the strike of Permian geologic units, which dip gently to the west-northwest into the Permian Basin. The 900 Hz coils are probably registering the subcrop of a natural brine-bearing unit.

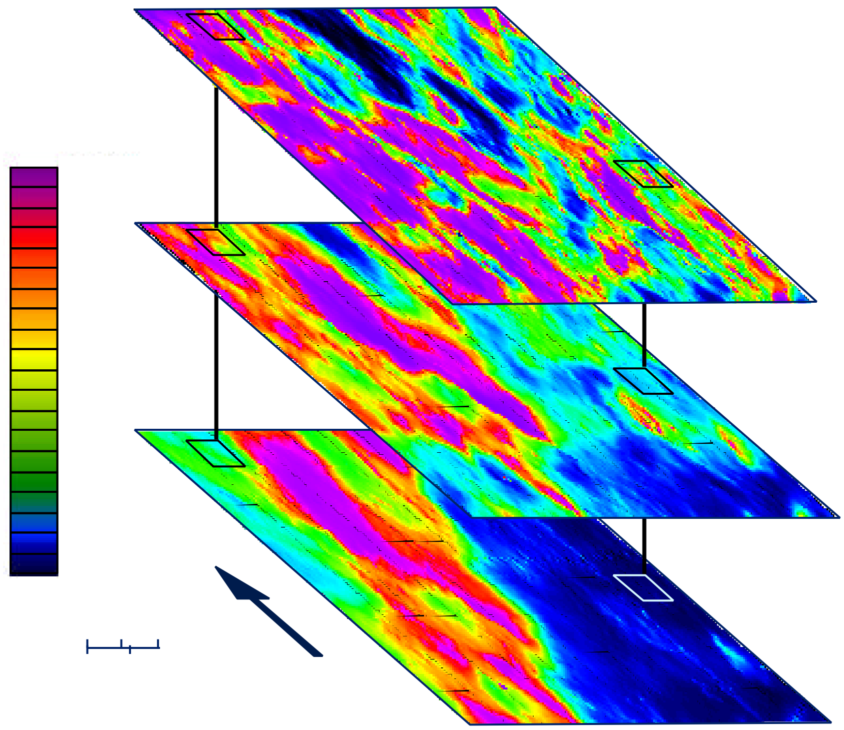

Figure 4. Progressively deeper images of ground conductivity in the Hatchel survey area as measured using airborne horizontal coplanar induction coils operating at 56 000 Hz, 7200 Hz, and 900 Hz. These images show numerous local conductivity anomalies, particularly at the higher electromagnetic frequencies. At site 76, where conductivity peaks on the 56 000 and 7200 Hz images correspond to a magnetic anomaly and a known well location, ground-based observations suggest the presence of a brine-leaking well. At site 17, a conductivity peak is present only on the 56 000 Hz image and is located near a known well and a magnetic anomaly. Ground-based investigations show this site to be an abandoned brine disposal pit.

Site characterization. We could not be certain from airborne geophysical data alone whether a given conductivity anomaly represented a leaking well, an abandoned brine pit, a natural saline spring, clay-rich or wet soil, an outcrop of a conductive geologic unit, or some other conductive feature. Field investigations that included ground-based geophysical surveys and soil and water sampling were completed at sites that represent the variety that would be encountered in most geophysical searches for oil-field salinity sources. The 56 000 Hz map had 103 sites with geophysical signatures that might reflect an oil-field salinity source. Ground-based conductivity profiles acquired at 21 representative sites allowed us to determine whether the conductivity anomaly was likely to be related to a leaking well, to brine that entered the subsurface through a nearby disposal pit, or to some other cause. Of the 21 sites investigated using ground-based methods, at least 8 are brine disposal pits and 4-6 are likely to be leaking wells.

A probable leaking well. Site 76, in the northwest part of the study area, appears as an anomalously conductive area on the maps of shallow (56 000 Hz) and moderately deep (7200 Hz) conductivity, but not on the 900-Hz map. The conductivity anomaly measures about 120 m east-west and 200 m north-south on the 56 000-Hz map and coincides with a magnetic anomaly. The site encompasses an abandoned well drilled in 1966 and plugged in 1975.

Ground investigations included single- and multiple-coil-separation conductivity profiles and TDEM soundings. Horizontal dipole measurements show well defined conductivity peaks at each exploration depth (Figure 5). Ground-conductivity measurements were used to construct a two-layer conductivity model (Figure 6). A low-conductivity layer on the east and west flanks of the abandoned well overlies a layer that has higher conductivity. The surface low-conductivity layer thins from about 4 m at each end of the line to less than 1 m near the well. At the well, the low-conductivity layer is replaced by a layer with a thickness of 2-4 m which is more conductive than the layer below it.

Despite the absence of surface evidence of brine leakage (no barren zone or brine at the surface), this plugged well is interpreted to be leaking and has been referred to the Railroad Commission of Texas for inspection.

An abandoned brine-disposal pit. Site 17, on the east of the test area, is defined by a large conductivity anomaly on the 56 000-Hz map. The anomaly is elongate northwest-southeast and measures about 200 × 400 m. Although there is a coincident magnetic anomaly, conductivities in the other two maps are not anomalously high. Aerial photographs and site visits revealed that the anomaly extends northwestward from an abandoned surface pit near an active well. Downslope from the pit is an area that is barren of vegetation.

Ground-based investigation consisted of single- and multiple-coil-separation profiles and TDEM soundings. The electromagnetic profiles confirmed the presence of a conductivity peak at the brine pit and adjacent barren zone (Figure 7). As coil separation increases, apparent ground conductivity decreases. This implies that ground conductivity decreases with depth, a conclusion supported by the TDEM soundings.

This wide variety of investigative techniques suggests that brine was once discharged into the pit and subsequently infiltrated into the shallow subsurface.

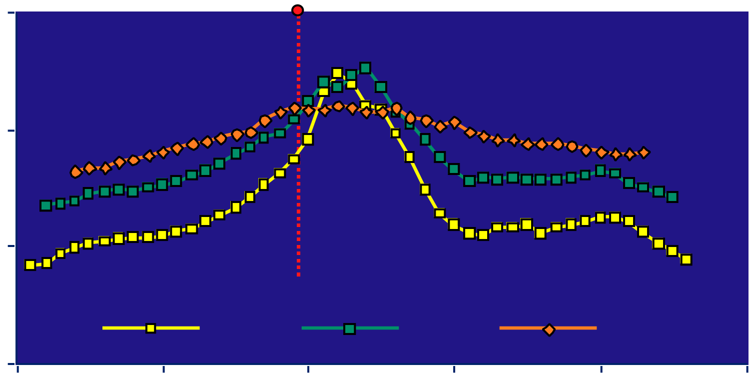

Figure 5. Apparent ground conductivity profile across site 76 measured using a ground-based induction instrument at 10-, 20-, and 40-m coil separations. Wider coil spacings correspond to deeper exploration depths. The line crosses the abandoned Vancil 1 well where a highly conductive zone is apparent at all exploration depths, is centered a few meters from the well, and broadens with depth.

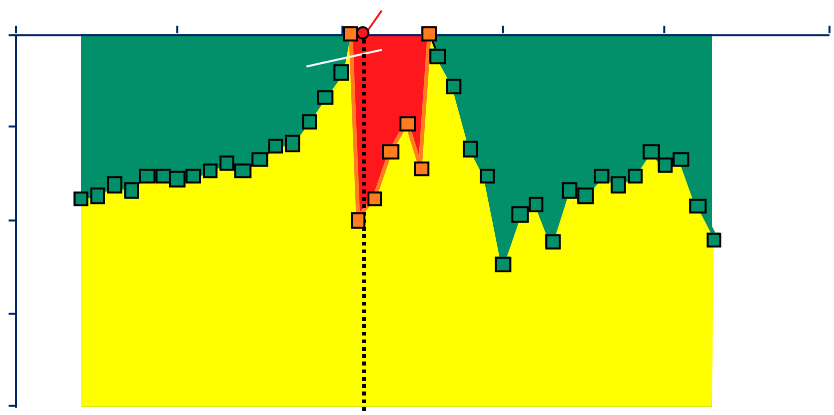

Figure 6. Two-layer conductivity model that fits ground-based electromagnetic data collected at site 76. Vancil 1 is flanked by highly conductive ground that represents a zone of saltwater infiltration. Although this well shows no evidence of brine leakage at the surface, on the basis of airborne and ground-based geophysical data, we interpret it to be leaking brine.

Profile of a leaking well. Ground investigation of several types of airborne geophysical signatures allows development of a “profile” of a well that may be leaking brine. This profile was developed for the Hatchel area but should apply wherever wells have steel casings and potential exists for upward brine flow through wells. Sites with an airborne signature that suggests an oil-field source are those that have (1) either a magnetic anomaly or a known well location and (2) anomalously high ground conductivity on both the shallow-exploring 56 000 Hz airborne coils and the deeper-exploring 7200 Hz coils. A suspicious site might also have a conductivity high on maps produced from the deeply-penetrating 900 Hz coils.

Follow-up ground investigations can reduce the number of anomalous sites to a list of wells that might be leaking. These investigations should include (1) precise location of the well through surface evidence or a magnetometer survey and (2) ground conductivity profiles that pass over or near the well site and other potential brine sources, such as surface pits or tank batteries. If a well has been leaking brine, measured conductivities should increase by a factor of 2-3 from background levels to maximum levels recorded within a few meters of the well. Wells that have been leaking for an extended period will generally have the highest conductivity peaks and the broadest areas of influence.

Conclusions. Geophysical surveys aid the search for near-surface salinization and can distinguish oil-field salinity sources from natural and agricultural ones. Airborne surveys cover large areas rapidly, provide context for sites, and reveal anomaly shapes. Although airborne magnetometers can detect subtle magnetic field changes caused by well casings, not every magnetic anomaly is a well and some wells might not be detect-

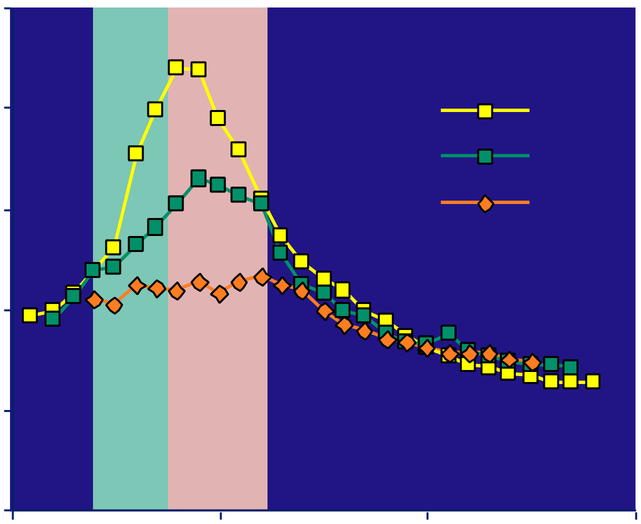

Figure 7. Apparent ground conductivity profile across site 17 measured using a ground-based induction instrument at 10-, 20-, and 40-m coil separations. The line crosses an abandoned brine disposal pit and an adjacent barren area. Unlike site 76, apparent conductivity decreases rapidly with penetration depth and suggests that the pit rather than a leaking well is the salinity source. Despite the passage of nearly 30 years since pit closure, the conductivity signature and barren area persist and the salinity plume has migrated less than 100 m laterally.

ed owing to flight-line spacing. The magnetometer nevertheless helps verify well locations and identify potential oil-field salinity sources, and it would be very useful where well locations are poorly known.

High frequency (56 000 Hz) airborne electromagnetic coils detected numerous conductivity anomalies across the study area. Many anomalies reflect soil changes or surface features such as brine pits, stock tanks, and streams. Deeper measurements from the low frequency (900 Hz) coils determined (1) whether the shallow anomalies had surface sources and (2) where brines might naturally infiltrate the near-surface environment. The frequencies most useful for locating potential oil-field salinity sources were 56 000 and 7200 Hz.

Ground-based geophysical methods verified airborne data, located actual well sites, and distinguished brine pits from possible leaking wells. These methods included magnetometer surveys to locate buried well casings, conductivity profiles to determine the likely salinity source and establish the salinization dimensions, and TDEM soundingsto determine plume thickness, explore deeper conductivity changes, and identify brine-bearing stratigraphic units.

Despite the success of the airborne method in locating wells and salinized areas, its widespread application is hindered by cost. Close line spacings that are required to locate magnetic anomalies associated with well casings and relatively small saltwater plumes make large surveys expensive. The optimum survey size for oil-field salinity sources is currently that of a typical oil field (few tens to a few hundred square kilometers). Less costly screening methods that might include analysis of remotely sensed imagery or airborne electromagnetic surveys of large areas at lower resolution are being considered for identifying sites where high-resolution surveys are warranted. LE

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