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16. Abstract

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This report does not contain sufficient detail to provide a strong working knowledge of some of the remote sensing methods. However, the references necessary to gain this working knowledge are included in this text.

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EXPLORATION MANUAL FOR AGGREGATES, TEXAS NE GULF COAST

by

Christopher C. Mathewson, Robert L. Lytton, Cynthia L. Cason, Samuel W. Gowan, and Mark A. Brotherton

Research Report Number 267-1F
Location of Marginal Flexible Base Courses
Research Study 2-9-79-267

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ABSTRACT

This report gives the results of a research project undertaken to locate sources of base course materials in the Gulf Coastal regions of Texas. The sites that were found are used as case studies to illustrate the principles of exploration for each of the different types of aggregate that were found, including sandstones, river gravels, and high gravels. The exploration always starts on a broad scale using maps, aerial photographs, and color-infrared images to delineate areas with a high potential for producing aggregates. The forms and shades of color that these deposits take on are different in wet, east Texas than they are in dry, southwest Texas. A more refined investigation is undertaken in the more promising areas using either seismic or resistivity techniques to delineate the depth and extent of the deposits. These techniques are explained so that the way they operate can be easily understood and put into practice. The final step in the exploration process is an actual drilling, coring, sampling, and testing program which will prove out the deposit.

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SUMMARY

This report gives the results of a research project undertaken to locate sources of base course materials in the Gulf Coastal regions of Texas. Three types of aggregates can be found in the area: sandstones, river gravels, and "high gravels." Specific sites were found which contained each of these types of aggregate and each site is used as a case study to illustrate the principles of exploration for these different aggregate types. Hard sandstone deposits are found along the Catahoula formation that stretches across the State roughly parallel to the Gulf Coast. Two such sites are illustrated, one in southwest Texas and the other in east Texas. River gravels were deposited either by the modern or the ancient river whose location can still be traced in the bedrock underlying the river bottom. The ancient Trinity, Neches, and Sabine Rivers were found to have carried much greater quantities of water and thus larger aggregates than do their modern descendants. A general rule was discovered in this project that a good place to search for river gravel is where a high gradient and a high degree of curvature in the course of the river coincide.

High gravels in east Texas are siliceous but are often called "iron ore" gravels because of their red and sometimes yellow colors. The red color comes from hematite and the yellow tint is due to limonite. These "high gravel" deposits are commonly found on hilltops, are located in the Willis and other closely associated

formations, and are found on the northern fringes of the outcrop belt.

Exploration for these aggregates always starts on a broad scale using maps, aerial photographs, and color-infrared images to delineate areas with a high potential for producing aggregates. The climate plays an important role in what to look for. In dry, southwest Texas, sandstones are located by looking for rectangular blocks and joints in which vegetation has taken root. In wet, east Texas, trees are less healthy when growing on sandstones that are close to the surface and appear as light-toned patches in a color-infrared image. The same is true of trees growing in deposits of the "high gravels" in east Texas. After locating the more promising areas, a more detailed on-site investigation is conducted using either seismic or resistivity techniques to delineate the depth and the extent of the deposits. The seismic technique is used with the sandstones and resistivity is used with the gravels. The final step in the exploration process is to drill or core, sample, and test the aggregate that has been located.

There is a clear explanation of both the seismic and the resistivity techniques in this report: how and why they work, how to interpret the data, what equipment to use, and so on. The report does not contain sufficient detail to provide a strong, working knowledge of the remote sensing methods. However, the references necessary to gain this working knowledge are included in this text.

IMPLEMENTATION STATEMENT

The material contained in this report gives the principles of exploring for three types of aggregates along the Gulf Coastal regions of Texas: sandstones, river gravels, and "high gravels." Several sites were located and are used in this report as case studies to illustrate the principles by which these aggregates can be found. The seismic and resistivity equipment that is used to delineate the depth and extent of a deposit is explained so that the way they operate can be easily understood and put into practice. At any time that D-9, the Materials and Test Division, or District personnel should require it, the methods presented in this report may be put to use to locate aggregates for flexible base course materials.

DISCLAIMER

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INTRODUCTION

Aggregates, such as crushed stone, sand and gravel, are important constituents in most construction projects. These materials are usually inexpensive when they can be found near the area of need. Historically, the Texas Gulf Coast relied on locally extracted aggregates, which were produced from sand, gravel, caliche, rock and oyster shell deposits that appeared to be haphazardly scattered throughout the region. These aggregates were used because they were either exposed at the surface or were accidentally detected while pursuing some other activity such as water well drilling or dredging of ship channels.

Recent population growths in southeast Texas have put a demand on aggregate resources that has far exceeded production. To compound this problem, oyster shells are no longer dredged from the Gulf Coast, due to environmental considerations. Today, the needs of the Gulf Coast of Texas are supplemented by limestone from the Cretaceous formations of central Texas (the sequence of geologic strata in Texas Gulf Coastal region is shown on Figure 1). The materials are shipped as far as 150 mi (Figure 2) at a freight cost that is running as high as 80 percent of the total cost of the aggregate. The building construction industry is able to absorb these higher costs by using alternate materials such as steel. When they must use aggregates, crushed stone can be shipped close to the construction sites by unit train because the sites are usually located at the urban centers that have railroad service. Unfortunately, highway construction must use aggregates and they also have a constantly moving point of need that can only be supplied by

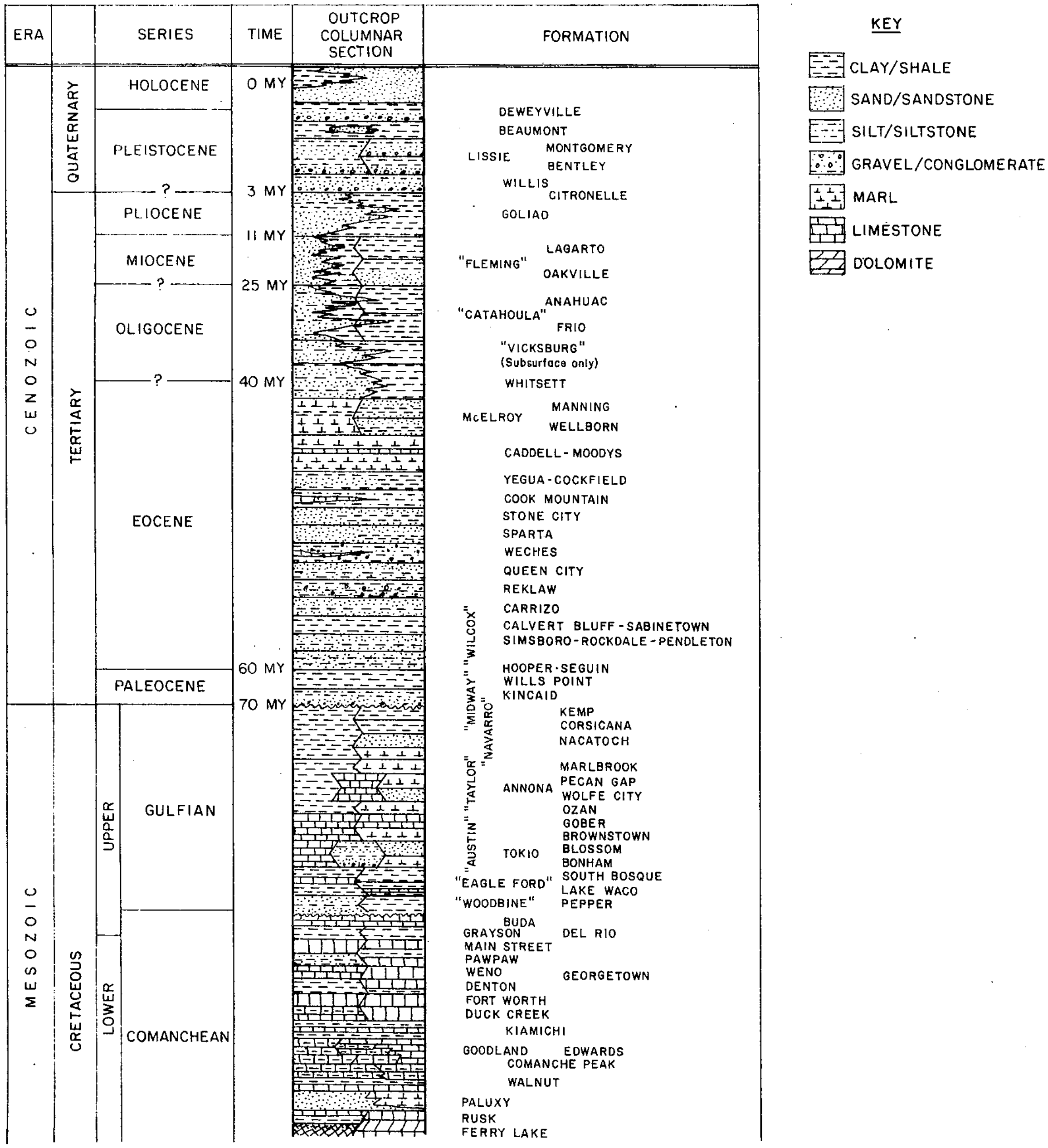


Figure 1. Sequence of geologic strata found in the Gulf Coast and central region of Texas.

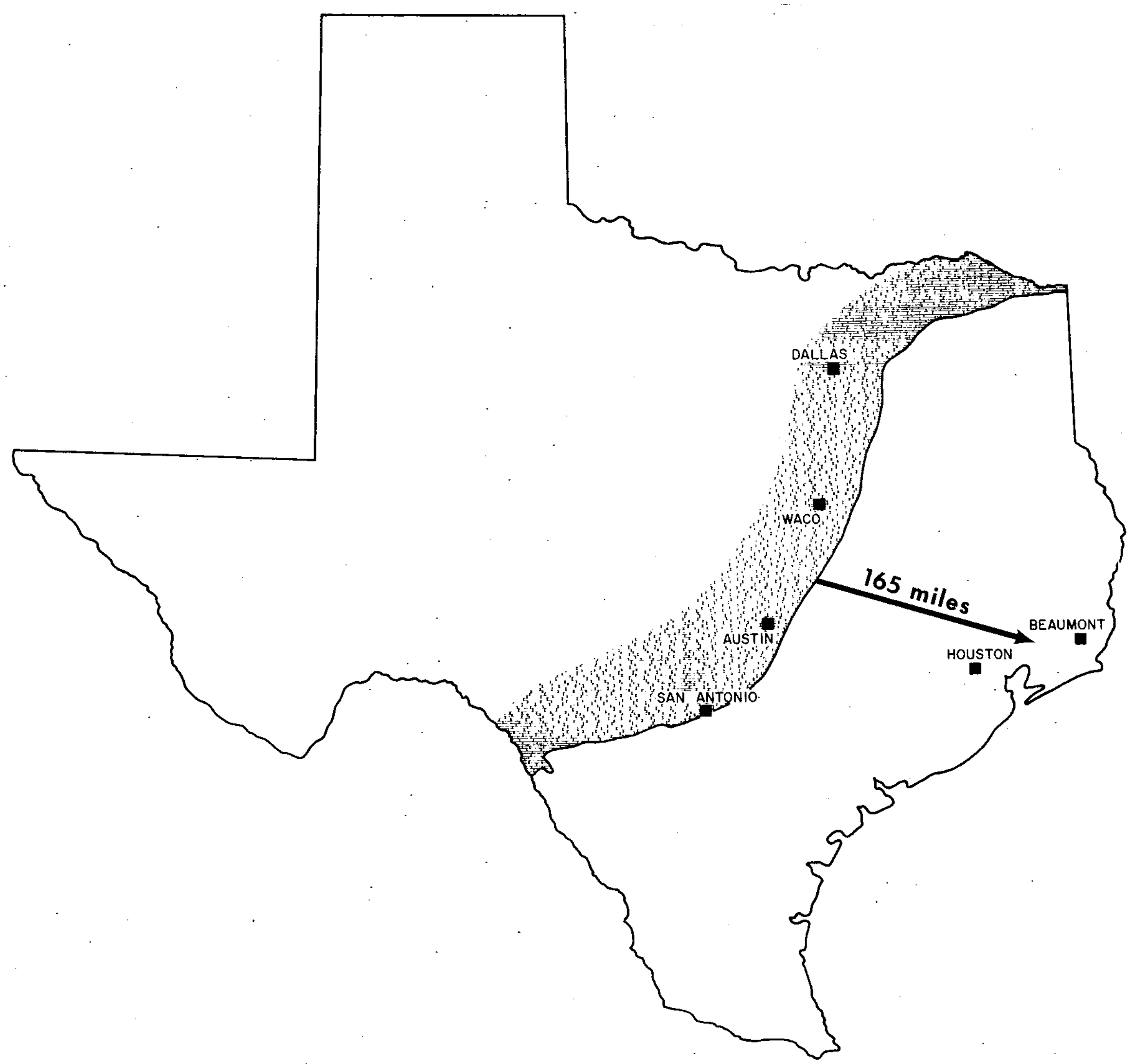


Figure 2. Minimum haul distance from the limestone producing Cretaceous Formation of central Texas to southeast Texas.

trucks.

Many people believe that there still is an abundant supply of aggregates in southeast Texas and that these aggregates are buried within the near subsurface. These aggregates can probably be located by using a well planned exploration program that involves geology, remote sensing techniques, and a drilling program.

SUMMARY OF AGGREGATE TYPES AND AVAILABILITY

In the past, the Texas Gulf Coast Region relied on several naturally occuring local aggregates. The aggregates were sandstone, sand, gravel, ironstone, limestone, oyster shells and caliche. Sand and gravel have traditionally been the most important, since these deposits were easiest to find and the most abundant. Sand and gravel can be obtained from two major sources, the Willis Formation and river terrace deposits.

The Willis Formation produces mostly sand, some siliceous gravel and minor amounts of iron nodules (Figure 3). Gravel and ironstone size and quantity decreases from west to east. River terrace deposits are more important producers of sand and gravel than the Willis Formation. Much sand and gravel has been produced from the Colorado, Brazos, Trinity and San Jacinto Rivers (Figure 3).

Sandstone is commonly found in the Catahoula Formation (Figure 3). A few minor sandstone deposits have been found within the formations of the Jackson Group. For example, the Yuma and Tuttle sandstone, part of the Manning Formation in Grimes County, have been used for county and

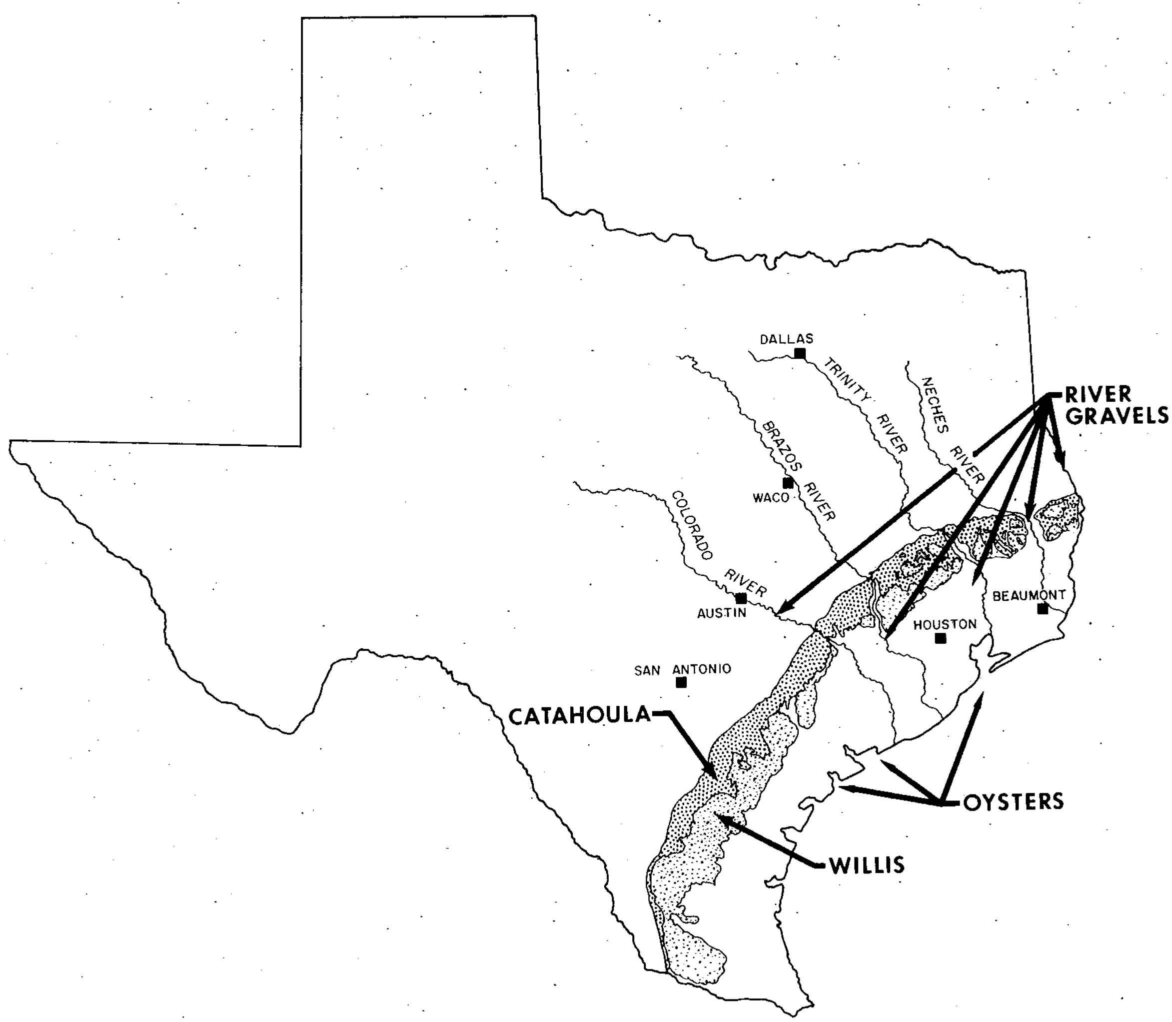


Figure 3. Sources of aggregate along the Gulf Coast of Texas.

private ranch roads.

Residual ironstone nodules are usually found in very thin, widespread, surficial deposits which are commonly located within the Weches, Reklaw and Willis Formations of east Texas (1). No single deposit produces a large volume, consequently this material can only be exploited on a local scale. The position of the Willis Formation is shown on Figure 3. The outcrop belts of the Weches and Reklaw Formations are found to the north and parallel to the Willis Formation, and they can be seen on the Seguin (2), Austin (3), Tyler (4), Waco (5), and Palestine (6) (Figure 4) sheets of the Geologic Atlas of Texas published by the Bureau of Economic Geology at the University of Texas in Austin.

Limestone deposits within the area are commonly associated with salt domes. Those deposits have only been of minor importance because the limestone cap rocks are often too deep to be economically mined. A good example is the Hockley Dome located near Hockley Texas in District 12, which is one of the shallower domes, with a cap rock 75 ft below the surface.

Oyster shells were dredged from the bays and lagoons along the Gulf Coast (Figure 3). As previously stated, this aggregate is no longer considered viable due to the damage that dredging causes to live oyster banks.

Caliche is an important aggregate in south and west Texas where it is predominantly used as a base course in residential developments and county roads. Although it is conveniently located for the cities along the Balcones Fault zone and in much of west Texas it is located far from

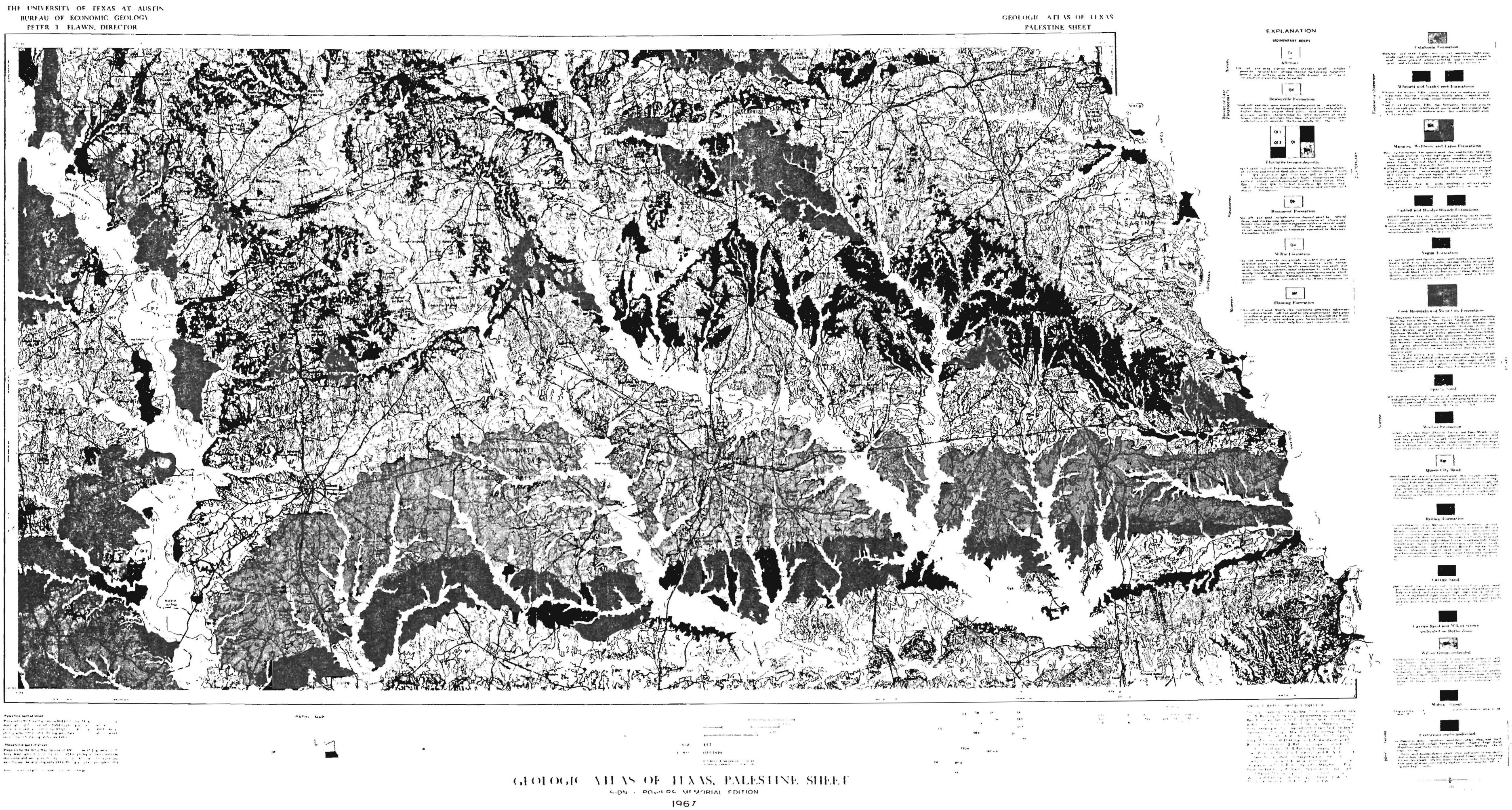


Figure 4. Photographically reduced copy of the Geologic Atlas of Texas, Palestine Sheet. These sheets are published at a scale of 1:250,000, in color, and are available from the Bureau of Economic Geology, Austin, Texas.

the major population centers along the Gulf Coast which need aggregates the most.

Sandstone, river gravels and high gravels (those gravels found associated with the Willis Formation) are the aggregates that seem to exist in large enough quantities to be economically important. This manual concentrates on describing the technology necessary to locate these three specific types of aggregate.

OBJECTIVE

The primary objective of this manual is to show how relatively inexpensive geological and remote sensing techniques can be used to locate sandstones, river gravels and high gravels in the Gulf Coastal regions of Texas. These techniques are explained so that the reasons they operate can be easily understood and put into practice.
However, a strong working knowledge of some of the remote sensing methods, such as geophysics, will probably require additional information that is beyond the scope of this document. The references necessary to gain this working knowledge are included in this text.

CEMENTED SANDSTONES

Cemented sandstones, which can be crushed to a durable aggregate for base course material, exist in the Gulf Coastal area of Texas. These cemented sandstones occur within the Eocene Catahoula Formation as well as a few other formations. The location and quality of the sandstones depends upon the environment in which the material was deposited as well as the type of cement which binds the sand grains.

Cement which binds sandstone layers ranges from clay to quartz (silica); sandstones cemented primarily with silica are the most important as aggregates. There are two theories as to how the sands became indurated (hardened) with silica cement. Paine and Meyerhoff (7) proposed that the cementation process is a surface phenomenon, referred to as "case hardening". The indurated beds are usually found relatively close to the surface, with the hardest portions in the upper ten feet of the sandstone. The cementation process occurs through solution and redeposition of silica in the voids. The silica probably existed in the matrix material, possibly a by-product of the breakdown of volcanic ash (common to this period of sedimentation in Texas).

Another explanation is that silica cement formed at the same time as, or shortly after, the deposition of the sand. Siever (8) points out that quartz and various forms of amorphous silica became available in solution by degeneration of volcanic glass and by abrasion of sand grains. This free silica may become trapped, concentrated, and subsequently precipitated as cement.

GEOLOGY OF THE CATAHOULA FORMATION

The Catahoula Formation is the predominant sandstone producing formation in the Texas Gulf Coast. It is represented by a topographically prominent and continuous outcrop belt that parallels the Gulf Coast shoreline (Figure 5). The Catahoula is a 250 to 300 ft thick sequence of friable sandstones, sands, siltstones, soft claystones, and occasional bentonite beds at the outcrop belt (7,9). The sandstones and siltstones are generally light gray to tan, are very soft

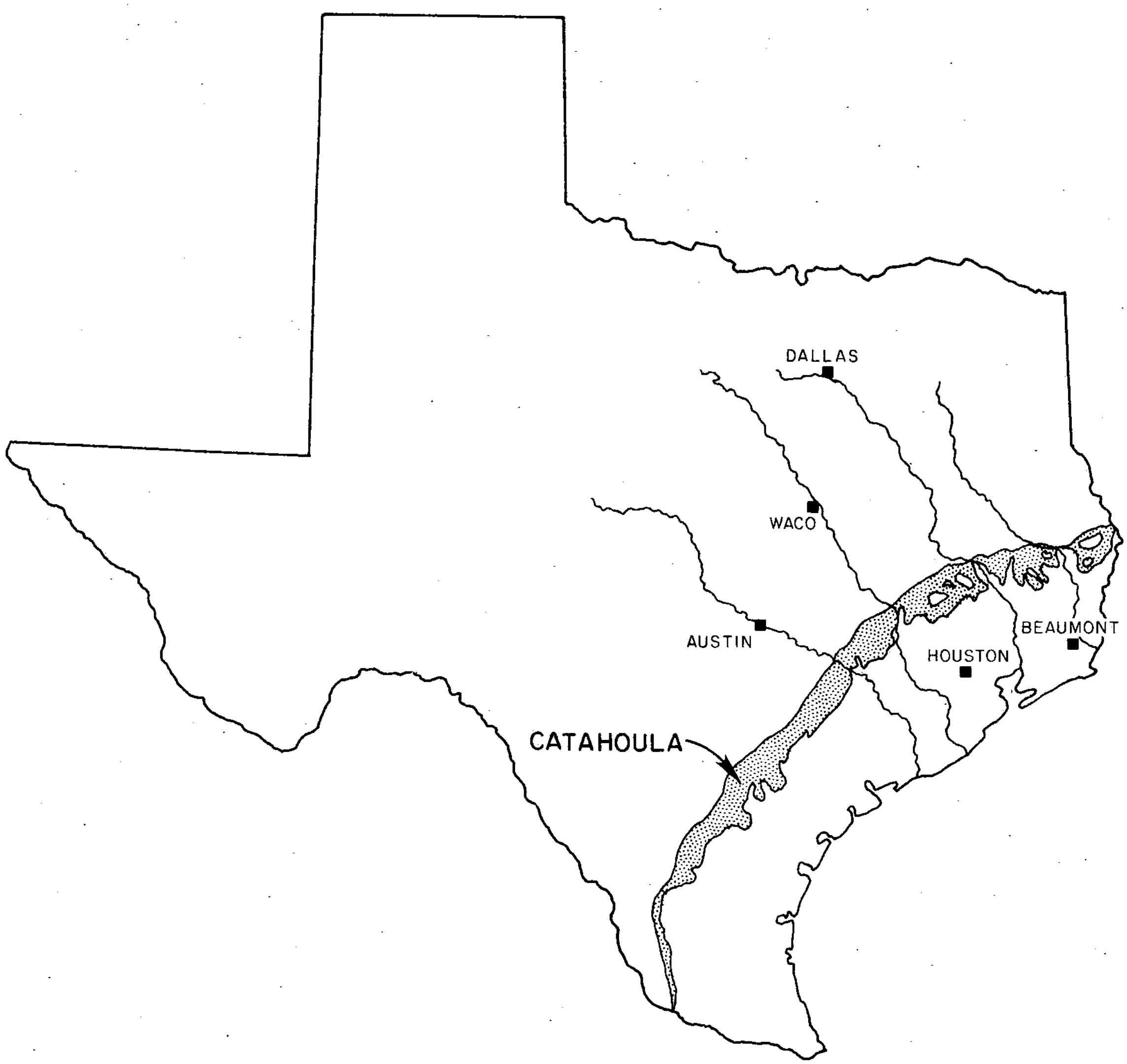


Figure 5. Outcrop belt of the Catahoula Formation.

to quartzitic, and have a cement that varies from montmorillonitic to opaline. The hard, quartzitic lenses that are important as aggregate have a discontinuous lateral distribution, are very erosion resistant, and have a well defined joint pattern.

The characteristics and distribution of the hard sandstones are a product of their environment of deposition. The Catahoula Formation was deposited under fluvial (stream) and lacustrine (lake) conditions during a time of great ash falls from a distant source (7,9,10). Galloway (9) recognized four basic depositional elements (or facies) from well logs and scattered outcrops in the region that he and others call the Chita-Corrigan Fluvial System, which is in the Houston Embayment. The four facies are interchannel lacustrine, well drained floodplain, fluvial channel fill, and crevasse splay (Figure 6). The crevasse splay facies is most important to this study.

A crevasse splay is a localized lobate tongue of sediment deposited through breaks in the levee system bordering a river. They are often coarser grained than the levee and other floodplain deposits and resemble small braided channel deposits. The crevasse splay facies can be divided into two subfacies - proximal and distal - of which the latter is by far the most important aggregate producing envrionment in the Catahoula Formation. The distal crevasse subfacies contains indurated, siliceous and tuffaceous muddy siltstone to fine sandstone as well as local lenses of poorly sorted medium sandstone. These deposits have a variable thickness but usually have a fairly large areal extent (9). Primary structures are nearly destroyed by root churning and shrink-swell attributed to

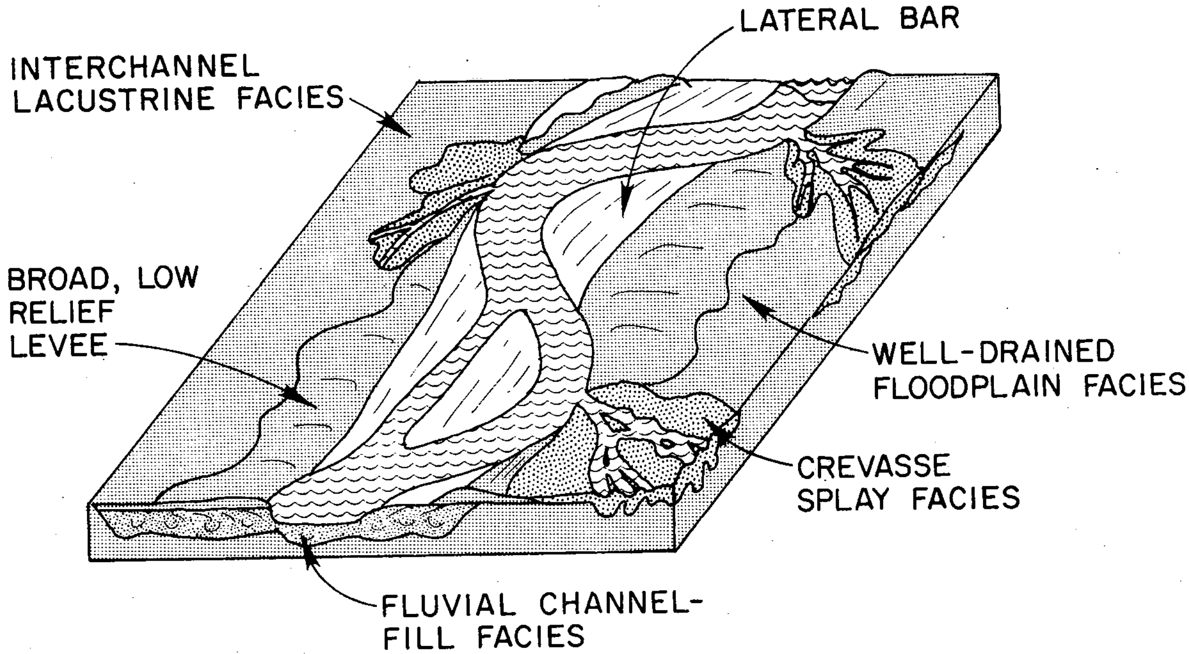


Figure 6. Schematic diagram of depositional elements found in the Catahoula depositional system (adapted from Galloway, 1977).

montmorillonitic soils. Montmorillonite is a by-product of the break down of volcanic ash. Some other important structures found in the distal crevasse subfacies are clay lined root tubules, spongy to vuggy (many open cavities) textures, clay coated fractures, filled mud cracks, and mud chips.

EXPLORATION TECHNIQUE FOR THE CATAHOULA FORMATION

Exploration for Catahoula Sandstone is accomplished using the following steps:

a. Initial location and evaluation of the outcrop areas;
b. Determination of high potential target areas;
c. Field reconnaissance;
d. Seismic evaluation of potential deposits;
e. Subsurface evaluation of high potential deposits.

These steps will be discussed in detail below.

Initial Evaluation

The initial exploration step for the Catahoula Sandstone involves location of the Catahoula Formation outcrop on a geologic map. The outcrop in southeast Texas (labeled "Mc") can be seen on the Beaumont, Palestine, Austin, Seguin, Beeville-Bay City, Crystal City-Eagle Pass and Laredo Sheets of the Geologic Atlas of Texas published by the Bureau of Economic Geology (Figure 4, pg 7). Sandstones will occur at or near the surface in the outcrop area, therefore, the outcrop belt must be investigated further to define potential sandstone producing zones.

High Potential Target Areas

High potential sandstone producing target areas can be delineated by using sand isolith maps, color infrared aerial photographs, and topographic maps. As mentioned in the previous section, the distal crevasse subfacies is the most important aggregate producing environment within the Catahoula. Sites of the crevasse splay deposition may be located on a sand isolith map. A sand isolith map is contoured with lines of equal net sand thickness in order to show sand distribution within the formation. Galloway (9) analyzed many geophysical logs in the Catahoula Formation and constructed the net sand isoliths based on this data. He found that the channel fill and other associated environments are stacked on top of each other. This stacking resulted in sand isoliths that indicate lenticular (lens-like) trends existing within the subsurface Catahoula. As a rule, only those isoliths of greater than 300 ft of sand thickness should be examined because these show the relative positions of the major channels that existed during deposition (Figure 7). The aggregate producing crevasse splay deposits should be located along the margins of these major sand channels. The present river systems tend to coincide with the ancient systems. This is logical because the modern rivers would follow the paths of least resistance, that is, they would form channels in the loose sand of the channel fill facies and be bordered by the hard sandstone of the crevasse splay facies. Field reconnaissance and drillhole data from the Texas Water Development Board, the Texas Board of Water Engineers, and the Texas Water Commission show that this is the case.

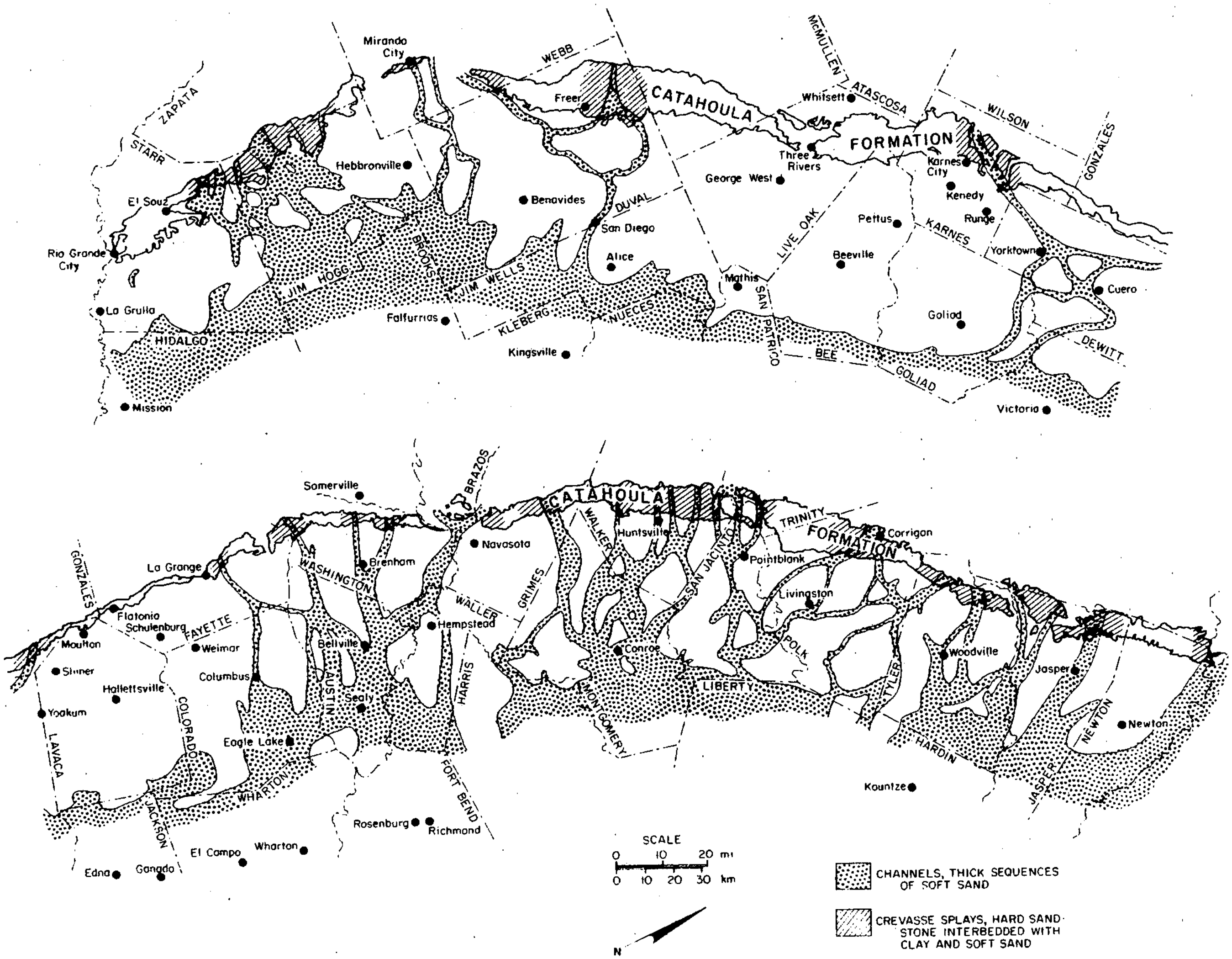


Figure 7. Sand isolith map showing distribution of sand within both the surface and subsurface portions of the Cahahoula Formation of east Texas (adapted from Galloway, 1978). Map also shows drill hole locations for drill data obtained from reports by the Texas Water Development Board, Texas Board of Water Engineers and Texas Water Commission. Drill hole data is tabulated in Appendix A (projection of subsurface sand isoliths by the author).

Crevasse splay deposits located on the sand isolith map are high potential sandstone producing zones. Exploration continues by inspecting color infrared (CIR) aerial photographs of these zones. CIR photos can be acquired through the Texas Natural Resources Information System in Austin, Texas. In east Texas, pine trees are not as healthy if they are growing on sandstones close to the surface. These less healthy trees show up on CIR photographs as pale red or light toned patches in a background of darker red produced by healthy trees (Figure 8). These conditions are most apparent on the photographs during spring and early summer during maximum growth of the vegetation. In south Texas, where the climate is less humid, the well defined joint pattern in the hard sandstone leaves its mark as rectangular blocks. The dark fringes represent healthy vegetation growing in the fractures which retain moisture during the dry months of summer (Figure 9). Sandstones can often be seen cropping out at the dark toned border. Photographs taken during late summer are usually the best since the soil is driest at that time.

Field Reconnaissance

High potential target areas selected using the above procedures must be field checked to determine the actual occurrence of sandstone. In addition, land ownership must be determined, and in the case of a promising prospect, access to the property must be acquired.

Seismic Refraction Evaluation

Overburden (soil) thickness and lateral extent of the sandstone at a particular locality may be estimated using seismic refraction techniques. This is possible because there is a significant siesmic

Figure 8. Reproduction of a C-IR aerial photograph of the surface of the Catahoula Formation in east Texas. The arrows are pointing to light toned patches that are locations where the sandstone is at or near the surface.

Figure 9. C-IR aerial photograph of the Catahoula Formation in south Texas. The thin arrows are pointing to the vegetation lined fractures. These form around a rectangular light toned central region marked with a triangle. The fat arrow marks a sand stone pit started in a fracture zone.

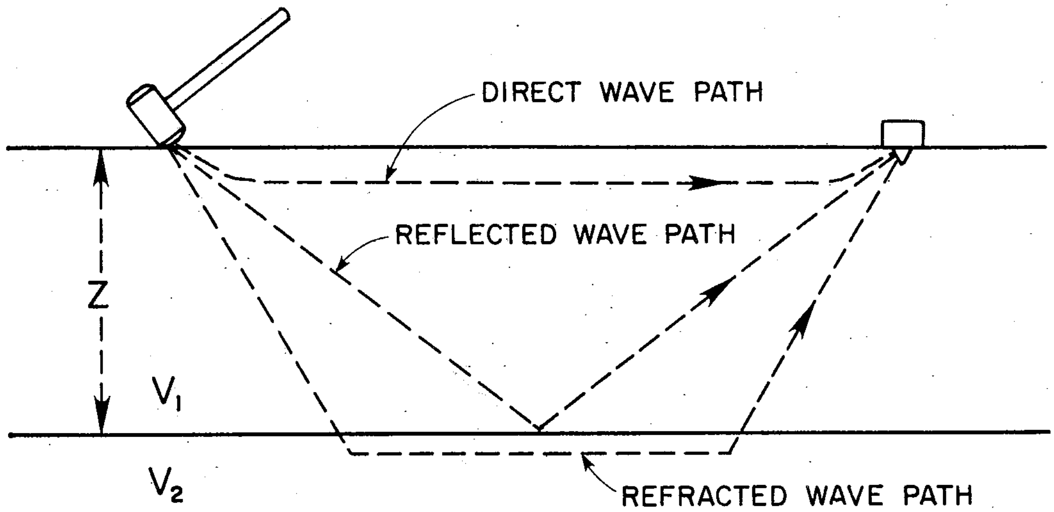
velocity difference between the overlying sediments and the hard sandstone. Seismic velocity is the speed with which an elastic wave passes through a material. The low strength overburden sediments have a lower seismic velocity than indurated sandstone. Seismic refraction is most valuable when there is a velocity increase downward, a sharp velocity contrast between layers, and the horizon of interest is shallow.

Theory of Operation of Seismic Refraction

The seismic method involves creation of a vibration or seismic wavefront at the ground surface. This wavefront travels out radially from the seismic source and is detected by geophones placed at varying distances from the source. Three types of seismic waves occur within the wavefront - compressional (P), shear (S), and Rayleigh waves. Of interest to engineering seismic applications are the P waves because they travel with the highest velocity. These are the first waves to arrive at the seismograph and the easiest to recognize and time. P waves cause slight compressional displacement of earth materials parallel to the direction of wave travel (11,12).

A simple example of the subsurface stratigraphy to be expected in the exploration for sandstone is a two layer arrangement as shown in Figure 10. The upper material has a seismic velocity (V_1) which is less than the velocity (V_2) of the underlying sandstone. Seismic velocity of the sandstone will increase with increasing induration. The interface will most often be shallow and roughly horizontal at an average depth (Z). Seismic waves propagating from the source travel directly through the upper medium or down to the interface where they are reflected

A



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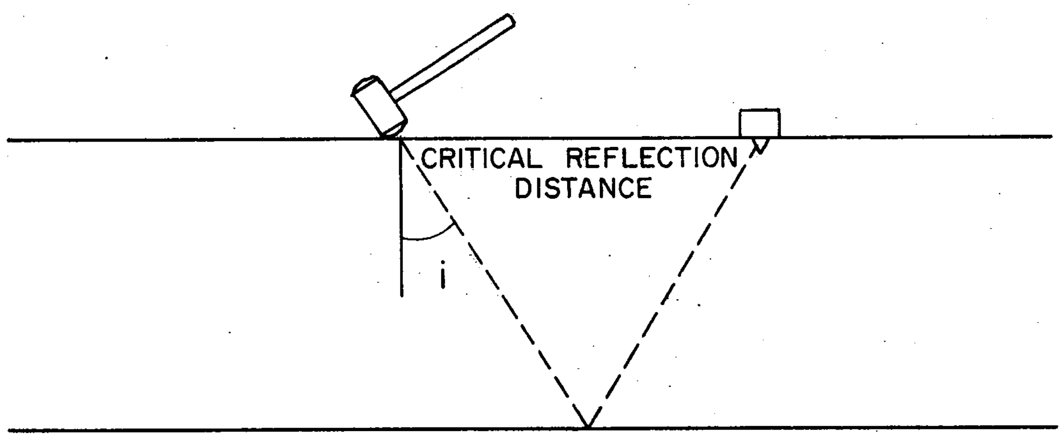


Z = AVERAGE DEPTH

V_1 AND V_2 = VELOCITIES OF HORIZONTAL LAYERS WHERE $V_1 < V_2$

i = ANGLE OF INCIDENCE

Figure 10. Direct, reflected and refracted shear wave paths in a single two layer case that is typical of the situation found in the Catahoula Formation. The V_1 layer represents unconsolidated overburden and V_2 represents the cemented sandstone.

and/or refracted. At a critical angle of incidence (i_c) waves are totally refracted; these waves travel along the interface in the lower medium propagating head waves (waves generated from waves moving along a surface) in the upper layer which return to the surface at the same critical angle. Waves striking the interface at angles less than the critical angle are partly reflected and partly refracted into the lower medium; those at greater angles are totally reflected. Of importance are the direct and critically refracted waves because these will be the first arrivals to the seismograph. Reflected waves arrive later and with a much smaller signal at these shallow depths of cover.

Measurements of seismic velocity are characteristic enough to permit lithological identification to a certain degree. Generally, the more dense the material becomes, the higher the seismic velocity it has. This will vary with mineralogy, cementation, and degree of fracturing. Table 1 lists a range of velocities to be expected for broad lithological types. Velocity of sediments overlying the sandstone should be within the first range and the sandstone itself within the second range.

Operating Technique for Seismic Refraction

Seismic refraction evaluation of the shallow indurated sandstone will require a seismograph, a seismic energy source, and one or more geophones. Figure 11 shows a single geophone seismograph and Figure 12 is a multi-channel seismograph. The refraction seismograph records first arrival travel time from the instant of wave propagation at the seismic source to the first wave arrival at the geophone(s). The geophone transmits an electrical signal to the seismograph which is amplified and displayed as a waveform either on a cathode ray tube screen,

Table 1. Range of Velocities for Rock Types

General Lithologic Type	Velocity ft/msec	Density g/cc
Clastic* Rocks, unconsolidated	1-6	1.5-2.2
Clastic Rocks, consolidated or cemented	5-12	2.0-2.6
Clastic Rocks in Orogenic Belts+	10-20	2.5-2.8
Metamorphic Rocks	15-20	2.7-3.0
Igneous Rocks	15-20	2.4-3.0
Limestone	10-20	2.4-2.7

(after Griffiths and King, 1965)

*Clastic = fragments of rack that have been removed from their place of origin. Particles can range from clay size to cobbles.

+Orogenic Belts = band of mountains formed by great pressures. Resulting rocks are compacted and well cemented.

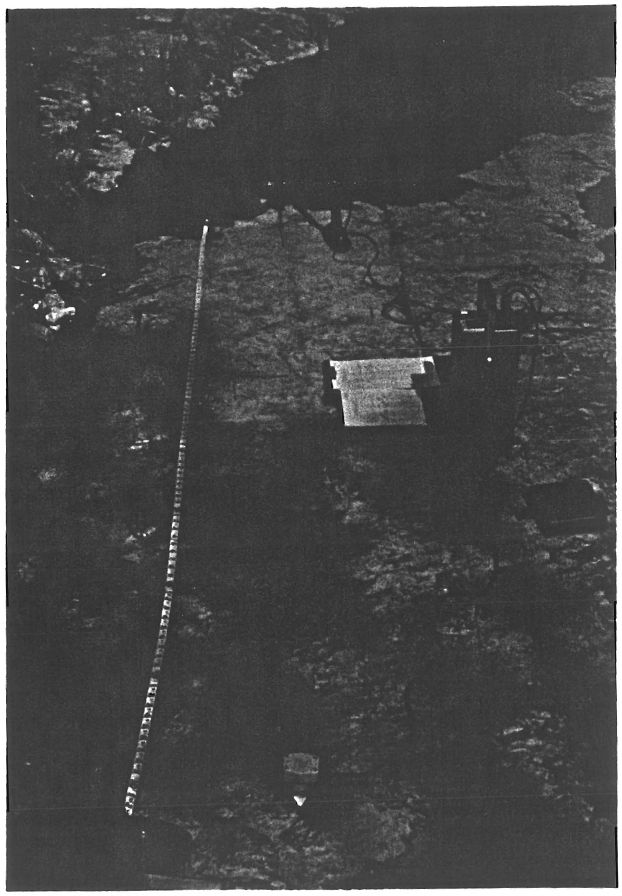


Figure 11. Photo of single channel seismic unit.

Figure 12. Photo of multi-channel seismic unit.

or as a digital readout, or as an oscillograph recording. Repetition of the energy impact enhances the amplitude of the waveform and also serves to cancel random seismic vibrations which might interfere with the first arrival signal. When a satisfactory waveform has been achieved, the first arrival point is located on the waveform (Figure 13). This occurs at the first break in the CRT trace. Travel time appears in digitized form or on a linear time plot. Data is plotted on a graph of first arrival travel time versus impact distance. Explicit field operation instructions are included with each type of equipment.

Several types of small single and multiple channel enhancement seismographs are appropriate for this exploration procedure. The enhancement feature requires extra circuitry to process and store the seismic signal and to add repeated signals for deeper siesmic evaluation with the same energy source. Single channel seismographs (such as the EG&G Geometrics Model ES-125 or the Bison Instruments Model 1570C) are used with a single geophone. These units are dependable up to depths of about 100 ft, are easy to operate and highly portable, and may require only a single operator. Multiple channel seismographs (such as the EG&G Geometrics model ES-1210F or the Bison Instruments Models 1580 and 8012) record information from an array of geophones and allow for an increased depth of penetration while they are still portable and easily operated. Some advantages of mulitple channel seismographs are: they produce a permanent record of the data, both mechanical and explosive energy sources may be used, background noise is further reduced and can be monitored, and they have a very high level of accuracy.

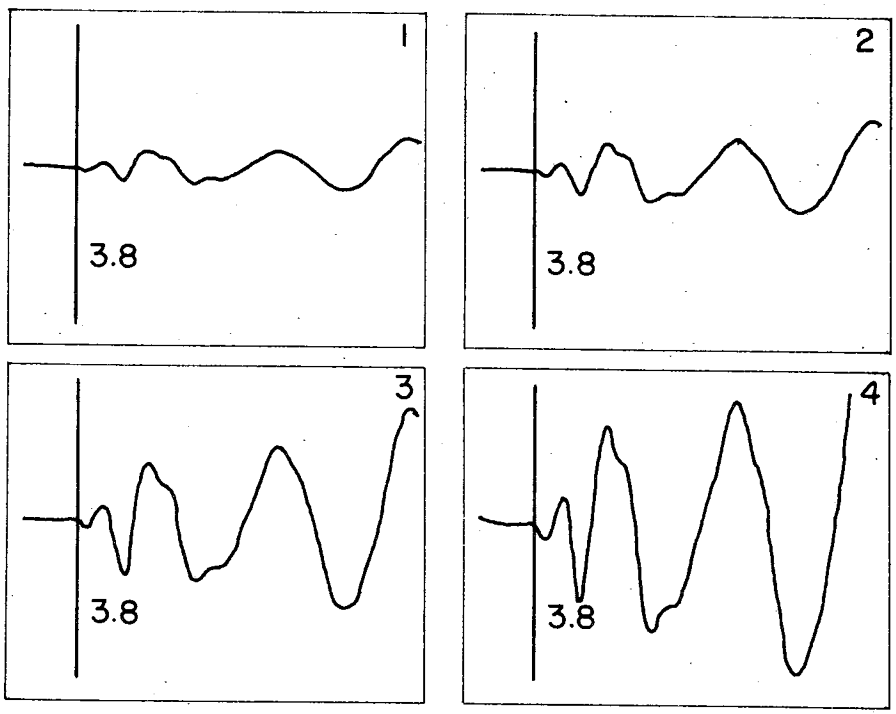


Figure 13. A sequence of CRT traces showing how successive hammer impacts can build a signal on a signal enhancing seismograph. The vertical line marks the first arrival and 3.8 is the time between impact and arrival.

The seismic energy source used to initiate the wavefront is commonly a sledgehammer and striking plate or a small explosive charge. The most important requirement of the energy source is to transfer a large enough amount of energy to the ground to produce a very sharp wavefront. Generally the hammer and striking plate will be used with the smaller single channel enhancement seismographs because it produces sufficient energy to penetrate up to 100 ft. An electrical switch on the hammer triggers the operation of the seismograph at the instant of impact. Impact conditions will cause the seismic survey results to vary. The strength of the hammer operator and the angle of strike will affect the amount of energy transferred to the ground. Strikes should be perpendicular to and in the center of the plate to achieve maximum effect. If the ground is soft, the cushioning will produce a smaller seismic signal with a longer travel time, and first arrival will be more difficult to determine.

Explosives require more extensive preparation, handling, and operator training. Each shot must be buried and fired separately. Special firing circuits are required to begin siesmograph timing. An explosion is an excellent seismic source and can produce the desired amount of energy in a sharp wavefront. These may be used when greater depth of penetration is desired, perhaps at the end of a line of hammer impacts.

The geophone is an electro-mechanical transducer which produces an electrical signal proportional to the vertical component of ground velocity; therefore, the geophone must be in an upright position to perform accurately. Generally, the geophone has a spike which can be pushed into the ground or removed for placement on solid rock. The geophone must be in firm contact with solid earth material. Wet clay produces the best contact while unconsolidated, dry material produces the poorest contact. Poor geophone placement may create signal distortion and increased noise levels. The geophone should be protected as much as possible from wind produced siesmic noise, perhaps by digging a small hole in which to place the geophone.

For a typical seismic survey, the geophone is at some point zero and impact points are spaced at regular intervals along a line away from the geophone. Impact spacing and line length will depend on estimated depth to the sandstone. Survey layout will depend on the expected areal extent of the sandstone as well as field conditions. Several parallel and perpendicular intersecting survey lines should be run and readings should be taken in the forward and reverse directions along each line. Reverse and intersecting surveys will permit cross checking of data. One or more surveys should intersect a drill hole if one is present in the area. Survey information should be tied to real data, either drill hole or outcrop, for comparison and interpretation.

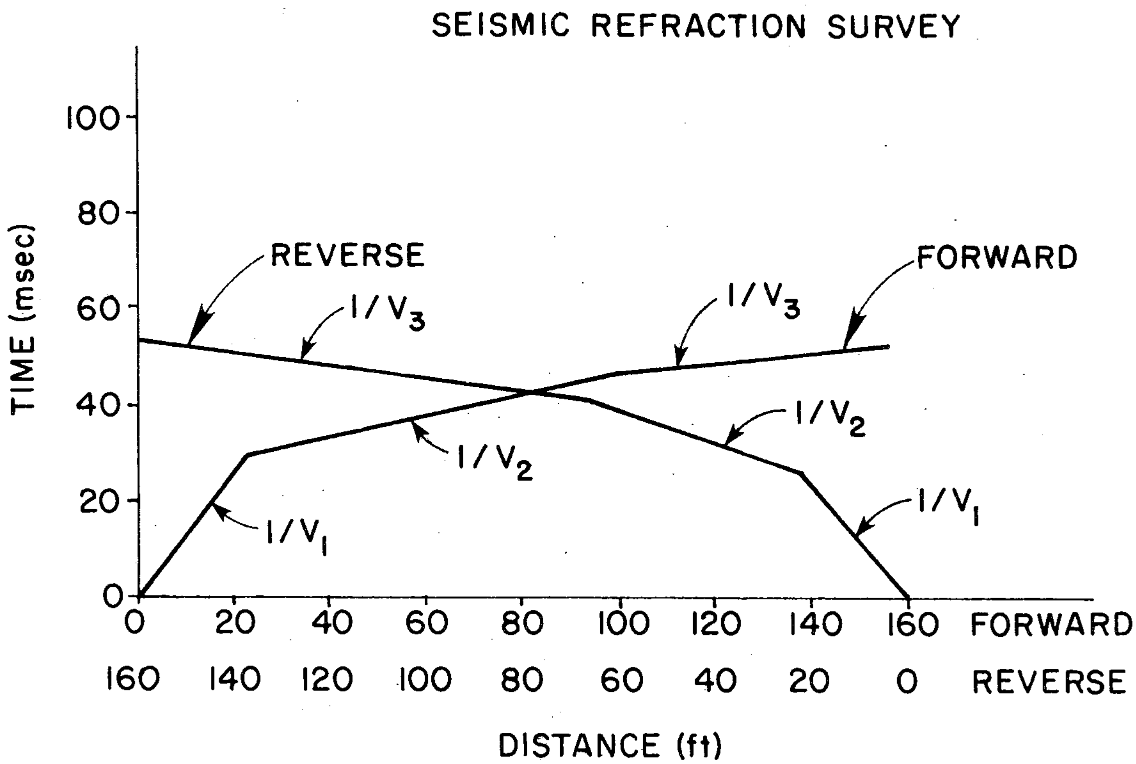
The intent of each survey is to locate the velocity boundary between the overburden and sandstone or to note its absence. The velocity change will be apparent in the field data, as will be explained in the section on interpretation. Because seismic refraction techniques cannot be used to determine the thickness of the sandstone body, several data points beyond the velocity change should be enough for individual surveys. Absence of the expected velocity change indicates that a boundary of the sandstone body has not been reached.

Interpretation of Seismic Refraction Data

The two layer, horizontally bedded subsurface structure described earlier is the simplest to use for interpretation purposes. In this structure, low velocity overburden sediments with velocity V_1, overly higher velocity sandstone with velocity V_2, and the velocity boundary is at an average depth (Z) beneath ground surface. Data points recorded in the surveys will most often reflect this arrangement. Each point is plotted on a graph of first arrival travel time versus hammer impact distance (Figure 14). The reverse survey data is plotted on the same graph. It should be possible to draw best fit straight lines through groups of points. Each straight line reflects a certain seismic velocity. Point scatter about the line may reflect inhomogeneities in the material or discontinuities along the boundary. One of the lines should intersect the origin. If there is no sandstone present, points will fall on a single line passing through the origin.

Lines V_1 and V_2 represent the seismic data for the two layers (Figure 15). T_i is the intercept time located by extending the V_2 line to the ordinate axis. X_c is the impact distance at which the two lines intersect. The seismic velocity for each layer is equal to the reciprocal slope of its representative line - dx/dT. Typical units of seismic velocity are in ft/sec or ft/msec. The above values are extracted from the data graph and are used to calculate the depth to the velocity boundary.

To calculate average depth to the interface, any one of the following formulae may be used:



$V_1 = 0.8$ ft/msec
$V_2 = 3.5$ ft/msec
$V_3 = 5.2$ ft/msec
$Z_1 = 9$ ft = Thickness of layer with velocity V_1
$Z_2 = 15$ ft = Thickness of layer with velocity V_2

Figure 14. Forward and reverse, time vs distance plots for a three layer case. The slopes of the lines are equal to the reciprocal of the velocity.

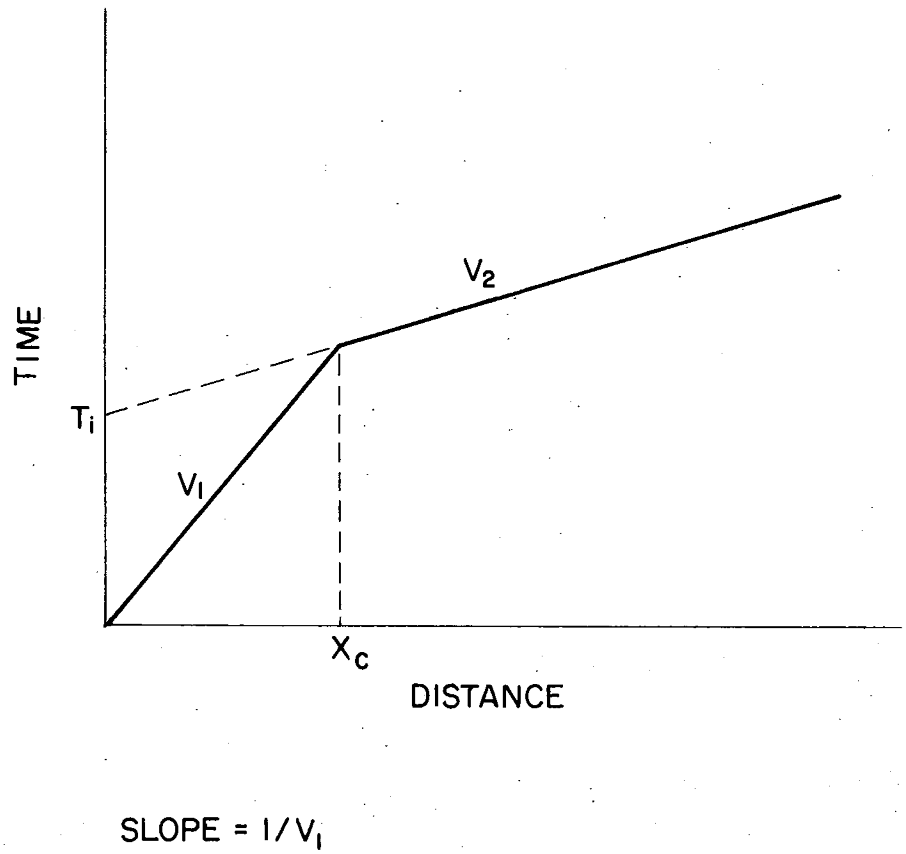


Figure 15. Simple two layer time vs distance plot showing how to measure the time intercept (T_i) and critical distance (X_c).

$$Z = \frac{V_1 T_i}{2}\left[\frac{V_2}{\sqrt{V_2^{\,2} - V_1^{\,2}}}\right] = \frac{V_2 T_i}{2}\left[\frac{1}{\sqrt{(V_2/V_1)^2 - 1}}\right]$$

$$Z = \frac{X_c}{2}\left[\sqrt{\frac{V_2 - V_1}{V_2 + V_1}}\right] = \frac{X_c}{2}\left[\sqrt{\frac{(V_2/V_1) - 1}{(V_2/V_1) + 1}}\right]$$

The average depth calculated applies to the portion of the interface along which the refracted wave travels.

If the sandstone body is dipping it will be apparent on the data graph by comparing forward and reverse data. The V_1 velocity line will be shorter in the direction of dip (Figure 16). Dipping layers will cause slight error in the calculations of velocity in the lower layer as well as in the depth to the interface. Approximate values can be calculated for the center of the seismic line by using the following equations:

$$X_c = \frac{X_{cF} + X_{cR}}{2}$$

$$V_2 = \frac{V_{2F} + V_{2R}}{2}$$

F = forward survey
R = reverse survey

The resulting velocity and depth values should be adequate for this exploration procedure, providing that the dip angle is not excessive.

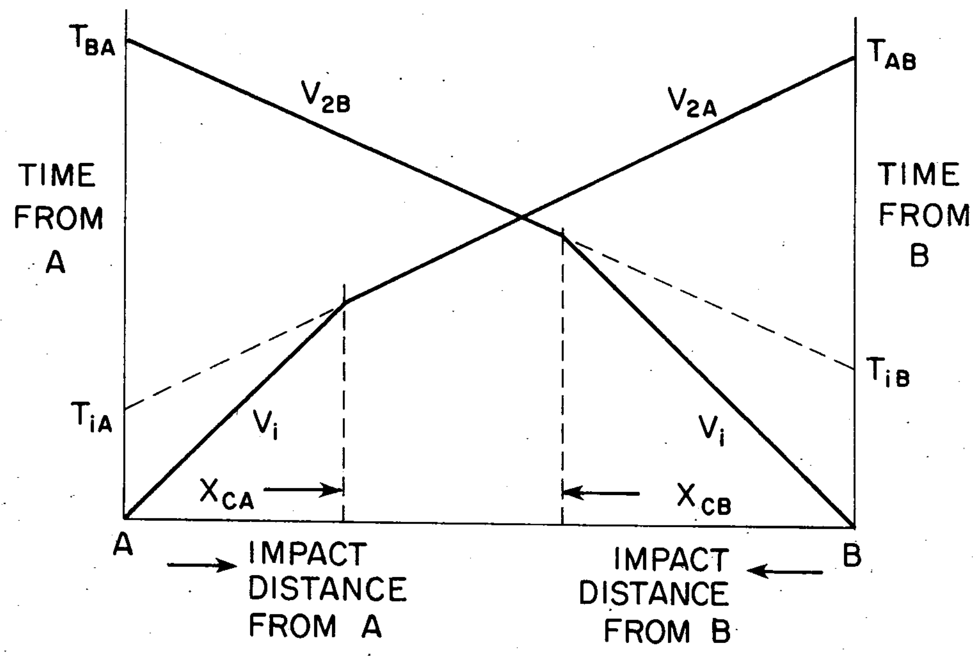


Figure 16. Forward and reverse surveys on a time vs. distance plot for a two layer case in which the lower layer is dipping toward B.

Expected error for all predictions based on shallow refraction seismic techniques ranges from 5 to 30 percent (11,12). From the seismic survey data, a rough depth-to sandstone map may be constructed. Subsurface exploration may be planned from the seismic evaluation to achieve optimum information.

Subsurface Evaluation

If the individual deposit continues to show substantial economic potential, the next step should be a drilling and coring program. Coring should begin near the outcrop and move away to detect gradual changes that may occur with distance from the outcrop. Cores should be continuous from the surface to well below the projected depth to sandstone in order to determine vertical variations in cementation and stratigraphy. A solid core is desired to obtain samples that can be quality tested and cross checked with the seismic data.

ADDITIONAL SANDSTONE PRODUCING UNITS IN SOUTHEAST TEXAS

In addition to the Catahoula Formation, a few other formations within the Texas Tertiary section contain indurated sandstones which crop out in the Gulf Coast. The Tertiary section is a highly variable wedge of predominantly fluvial-deltaic sands, silts, and clays extending from the Paleocene Midway Group to the Pliocene Goliad Formation (Figure 1, page 2). Cemented sands are generally referred to in the literature as beds or lenses of somewhat limited extent. Cementation processes and extent will vary with each formation as well as on a local level. Exploration for these sandstones should commence with a literature evaluation. High quality data such as that produced by Galloway (9) on the Catahoula Formation may not be available for every formation, however, significant resources are available to produce desirable results in many cases.

RIVER GRAVELS

Siliceous gravels that have been concentrated in alluvial valleys of Gulf Coast rivers are another source of aggregate in Texas. Gravel is naturally broken rock and mineral fragments greater than about 0.24 in in diameter which may be angular to rounded in shape. The quartzitic composition of gravel found in the Gulf Coast makes it very durable and therefore highly acceptable as base course material, except when it is used in a bituminous base material and stripping becomes a problem.

GEOLOGY OF RIVER GRAVELS

Sources

The ultimate sources of gravel in the Gulf coast area were mountains in New Mexico and Colorado and the Cretaceous limestones of central Texas (Figure 17). Debris from the mountains in New Mexico and Colorado was concentrated in the Ogallala Formation of the high plains area which now supplies gravel to the Texas Gulf Coast (13). Cretaceous limestones supply large quantities of chert to the southern rivers and minor quantities to the southeastern rivers. Southeast and south Texas receive coarse grained material directly from the above sources as well as from the gravel bearing Willis Formation.

The Tertiary Ogallala Formation is a land surface deposit of coalescing alluvial fans which extends from South Dakota to the southern panhandle of Texas. Composition of the Ogallala averages 7 percent gravel and conglomerate, 70 percent sand (quartz, quartzite, and some feldspar) and 23 percent clay. These sediments contributed a major

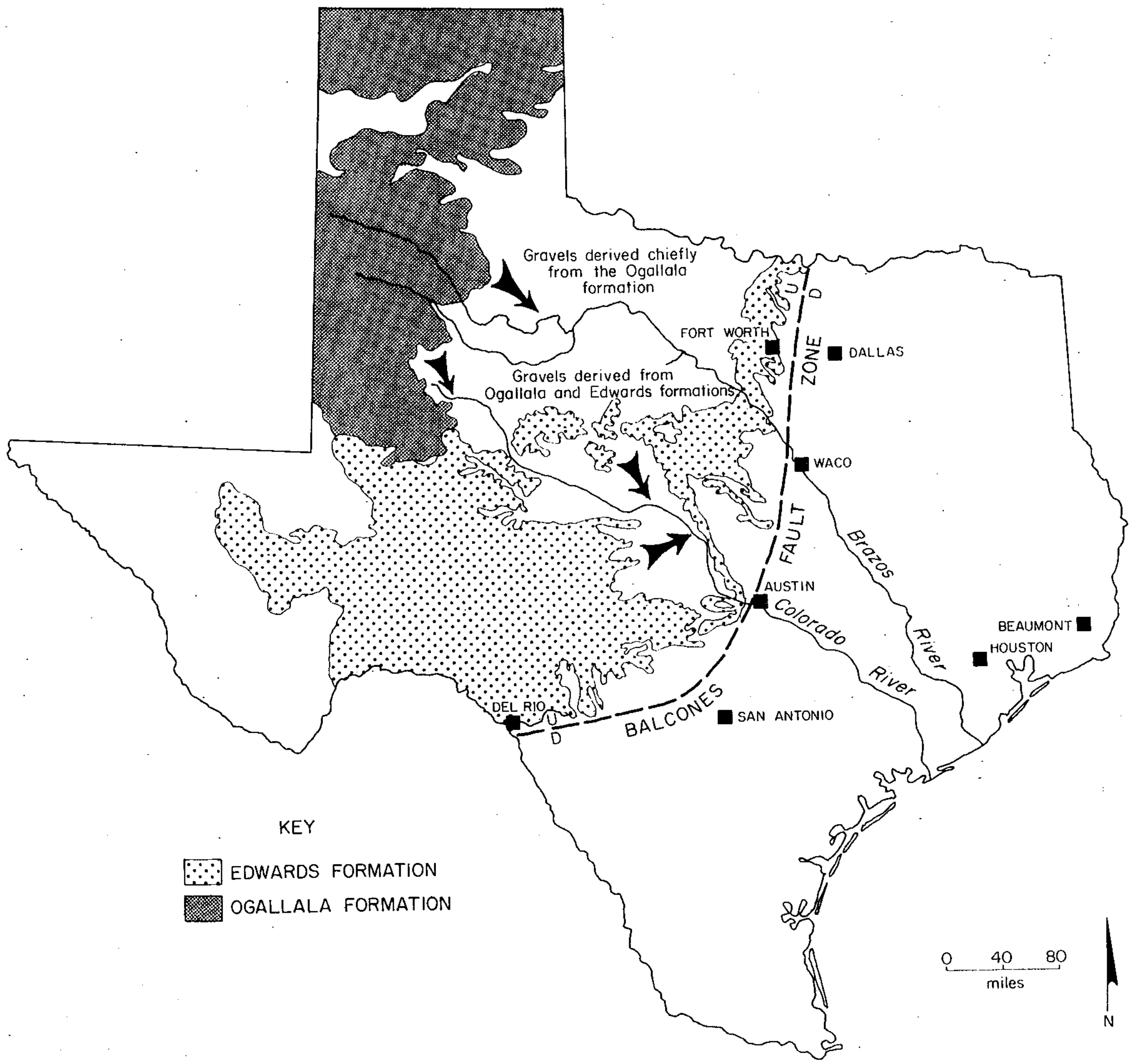


Figure 17. Sources of gravel for Gulf Coast rivers.

portion of early floodplain deposits to the east of the outcrop (14).

The Cretaceous Edwards Limestone produces most of the cherty gravel found in southeast and south Texas. Chert occurs as nodules or flattened lenses oriented parallel to or along bedding planes in the limestone. They range in size from quarter inch nodules to lenses over three feet long and up to a foot thick. The chert is bluish-black to brownish-black and exhibits concentric banding (15).

Since these source rocks are located primarily to the north and northwest of the area of interest, the quantity of gravel to be found in Texas river valleys decreases towards the east. This trend is also reflected in the Willis Formation as percentages of gravel decrease eastward. Generally, river floodplain deposits east of the Balcones Fault Zone (Figure 17) are influenced mainly by well rounded quartz and quartzite gravels of the Ogallala Formation, while to the west river deposits show more influence from Cretaceous cherts (14).

Sites of Gravel Accumulation

Sites of gravel accumulation in a river valley are controlled by the physical processes forming the deposits. There are several generic deposits which include: 1) point bars associated with meander cutoffs, 2) simple valley fill, 3) gravel concentrated in a channel produced by local influx from bed load streams, 4) nickpoint accumulations and 5) gravel concentrated on the downstream side of growth faults.

The most obvious accumulations of gravel occur in recent or ancient point bars which make up floodplain and terrace deposits. Point bars are arc-shaped (arcuate) features which form on the inside of meander bends of active river channels (Figure 18). The point bar surface dips toward the river channel and is often characterized by ridge and swale topography (Figure 19). These features begin forming as a coarse channel deposit, and as the channel migrates outward against the cutbank, the initial deposit is buried by progressively finer and finer material (Figure 20). Point bars are typically composed of distinctive layers that start with gravel or the coarsest available material at the base, and grade upward through sand, fine sand, silt, and clay of overbank floodplain deposits. Schumm (16) demonstrates that the coarsest grained material is initially deposited on the upstream end of a point bar, consequently this is where the best gravel deposits are located. As the river shifts within its meanderbelt, meander loops may be cut off or abandoned. These relict structures act as storage areas for coarse grained point bar deposits.

The remaining four types of sites of gravel accumulation are not as obvious since they have no distinctive surface expression. For example, simple valley fill occurs when the coarsest materials are deposited within the deepest parts of the channel. These are subsequently covered by a blanket of finer grained floodplain deposits. This sequence was made possible in Gulf Coast rivers, especially the Colorado and Brazos Rivers, by the glacial periods existing during the Pleistocene. During the onset of glaciation, sea level dropped resulting in intense downcutting by Gulf Coast rivers. As the ice sheets receded and sea level rose, the streams were gradually filled in. Grain sizes decreased upwards due to gradual flattening of gradients and reduction of the

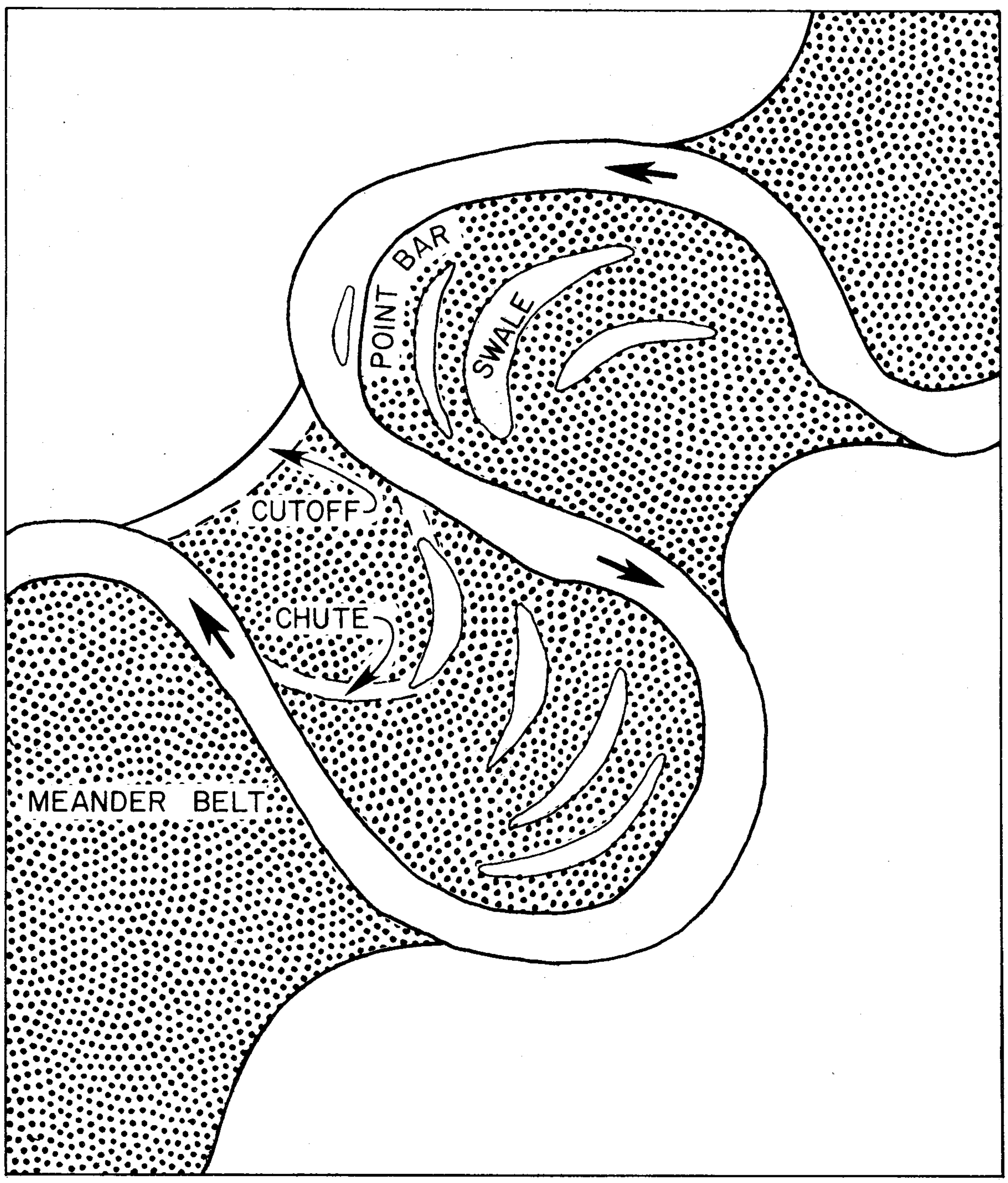


Figure 18. Schematic plan view of point-bar deposits.

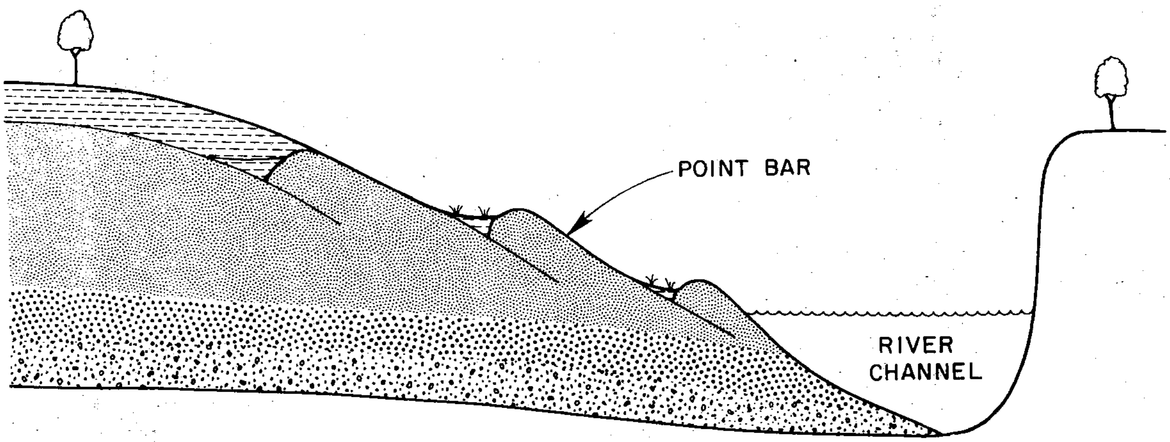


Figure 19. Schematic cross section of a typical point-bar deposit.

Figure 20. Point-bar deposit on the Colorado River near Garwood, Texas.

power of the river to transport aggregates.

Gravel deposits are also formed where a major suspended load stream (stream transporting only silts and clays) is joined by a smaller tributary that transports gravel. The transport power of the major river is not sufficient to move the gravel (Figure 21). The stream transporting gravel will naturally be characterized by a steeper gradient and higher flow energy than the suspended load stream. Where it enters the main trunk stream, the tributary will push the trunk stream toward the valley wall opposite from where the tributary enters (16) and most of the coarsest grained sediments will be deposited in the vicinity of the juncture.

Nickpoint and growth fault deposits are very similar in appearance and both occur where a stream suddenly loses gradient. Nickpoints form when a stream flows across rock of different erosional resistances. Some strata are of sufficient resistance to act as a local base level and prevent the upstream bed from downcutting very rapidly while downstream rocks are deeply incised. As a consequence, a nickpoint or a waterfall will form in the river where the two formations are in contact (17). A wedge of coarse grained detritus may form downstream from the nickpoint if the stream begins to infill (Figure 22). Growth faults produce similar deposits if the fault is perpendicular to the channel and subsidence occurs on the downstream side contemporaneously with deposition (Figure 23).

EXPLORATION FOR RIVER GRAVELS

Exploration for river gravels involves the use of two distinctly

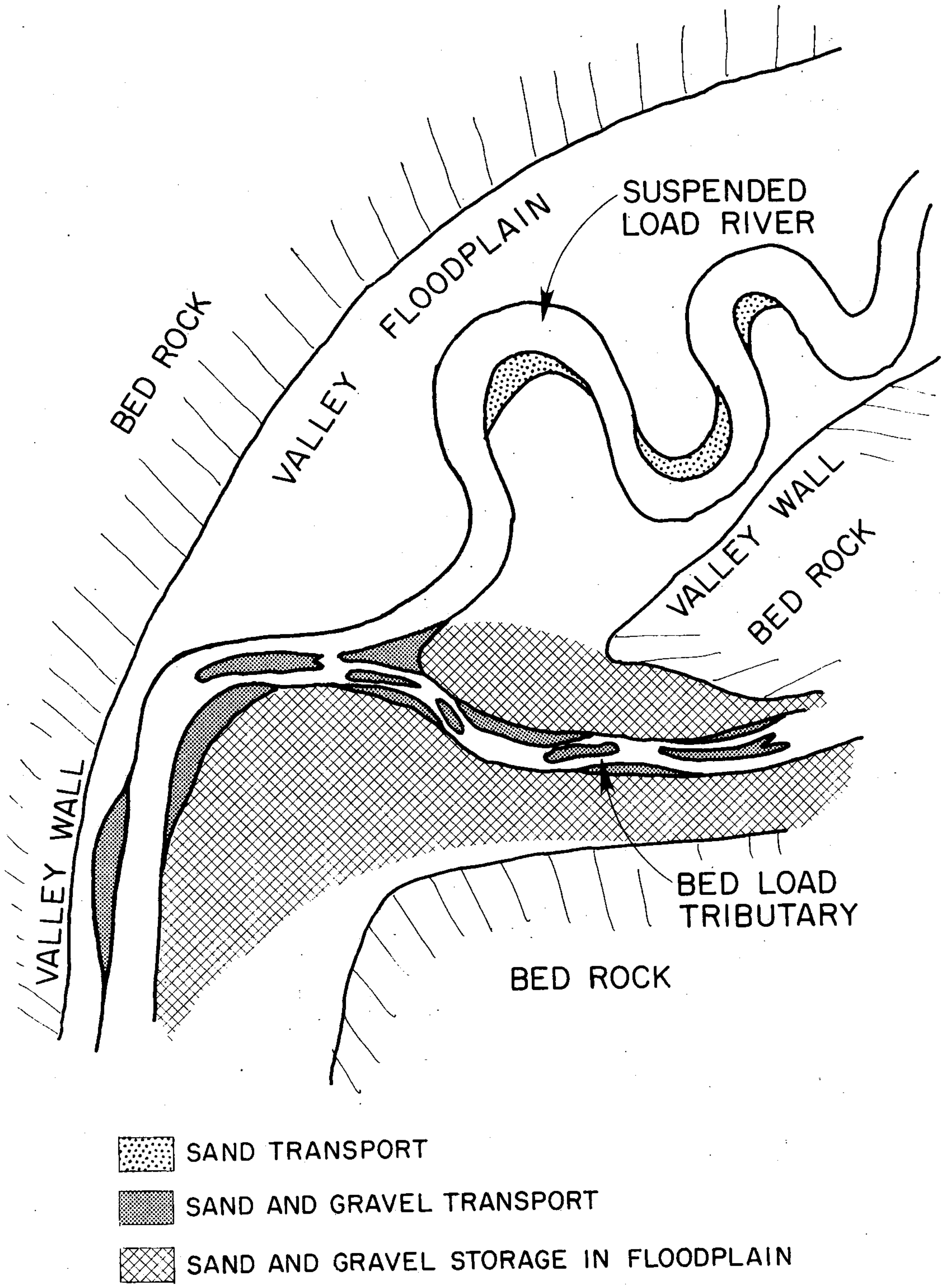


Figure 21. Distribution of sand and gravel deposits at the juncture between suspended and bed load streams.

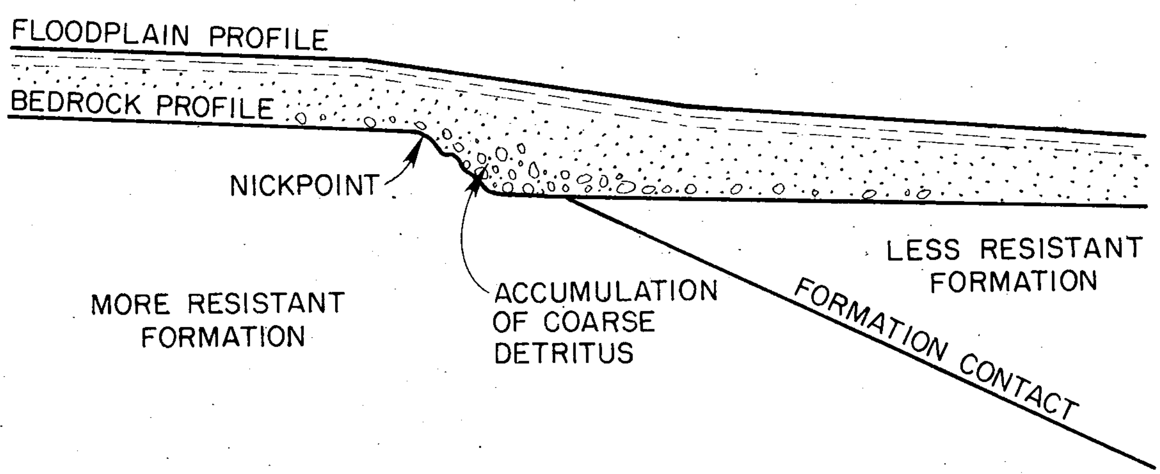


Figure 22. Gravel accumulation downstream from a nickpoint.

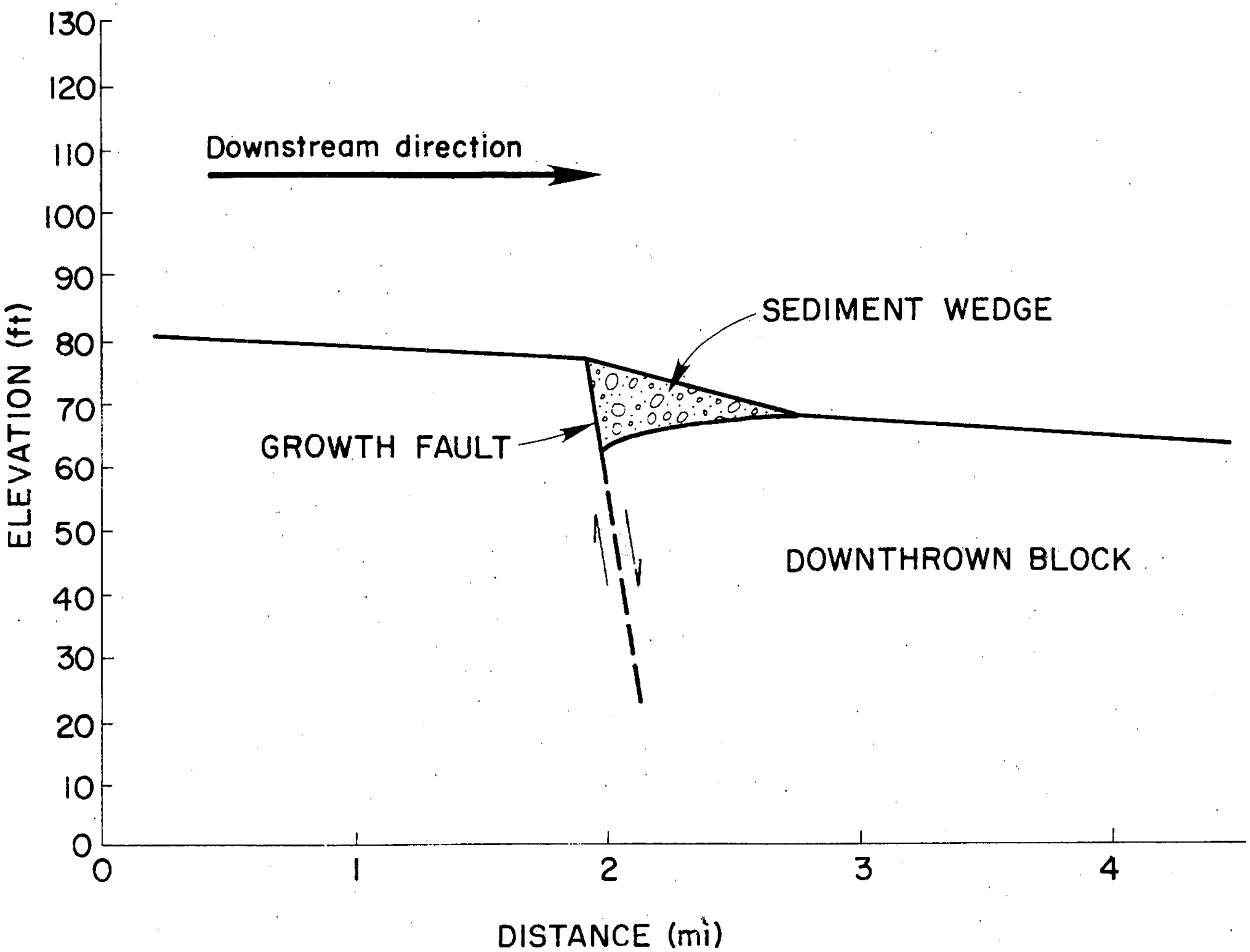


Figure 23. Gravel accumulation downstream from a growth fault.

different approaches. One approach uses the geomorphology of point-bars to locate deposits, since point-bars have a very distinctive shape and often have a well defined surface expression. The other method relies on quantitative measurements of a modern stream to relate recent surface morphology to subsurface conditions.

A basic exploration program for locating river gravel involves the following steps:

a. Determine whether or not a river is a potential aggregate source.

b. Select high potential target areas

   i. Look for point-bar deposits

   ii. Look for buried channel fill, tributary influx, nickpoint and growth fault deposits.

c. Evaluate with electrical resistivity.

d. Sample.

Determination of the Potential of a River as an Aggregate Source

The first step in any exploration technique for river gravel is to determine whether or not a river is a potential source of gravel in order to eliminate time wasted on a barren river. This step can be simplified if there are known deposits existing along the river. This information may be obtained by locating existing or abandoned gravel pits on county maps, quadrangle maps, aerial photos or from drill hole data. Sand and gravel have been and are being mined along many of the rivers in southeast and south Texas.

Rivers that do not have known pits must have sufficient terrace deposits to contain large gravel deposits; they must have a source of gravel; and they must have, or have had, high enough energy sometime in their past to transport gravel. It is difficult to prove the transport power of an ancient river system without analyzing the actual grain sizes. However, Leopold and Wolman (18) and Schumm (16) show that comparisons between streams can be made based on radius of curvature, meander length, channel width, and discharge (Figure 24). This information can be taken from topographic maps which show modern streams and channel scars of the ancient streams.

As an example, measurements of radius of curvature, meander length, and channel width were taken along the gravel producing Sabine and Trinity Rivers as well as the Neches River, which is not known to be a gravel producer (Figure 25). Both active channels of the modern streams and inactive channels of Pleistocene streams were measured and the results are presented in Table 2. Plotting this data on Leopold and Wolman's (18) meander length versus channel width and mean radius of curvature graphs (Figure 26) reveals that the ancient river systems appear to have been of similar dimensions and character. This is also true for the modern rivers which are slightly smaller. When the data is plotted on Schumm's (16) meander length versus discharge curve (Figure 27), the three ancient rivers plotted between 100,000 and 500,000 cubic feet per second with the Trinity being the highest. These results indicate that the ancient Neches River was just as capable of transporting gravels as were the Sabine and Trinity Rivers. The Neches River also has associated terraces of sufficient size to contain large gravel deposits.

This evaluation of river potential is a very important step in gravel prospecting. After it has been determined that a river has the

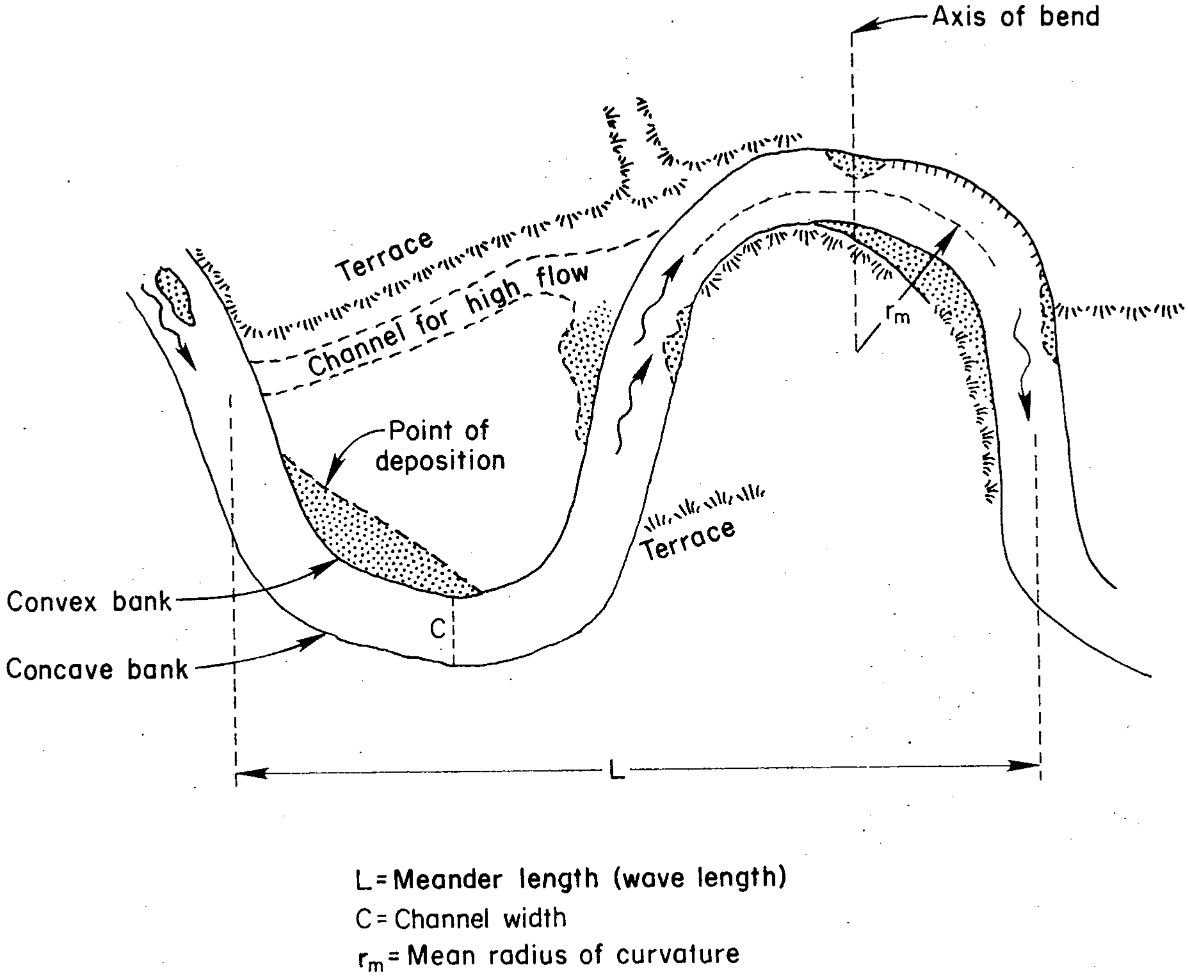


Figure 24. Plan view of a river meander showing dimensions of length, radius of curvature, and channel width. Deposition on the upstream end of the point-bar is characterized by coarse grained sediments and fine grained sediment on the downstream end.

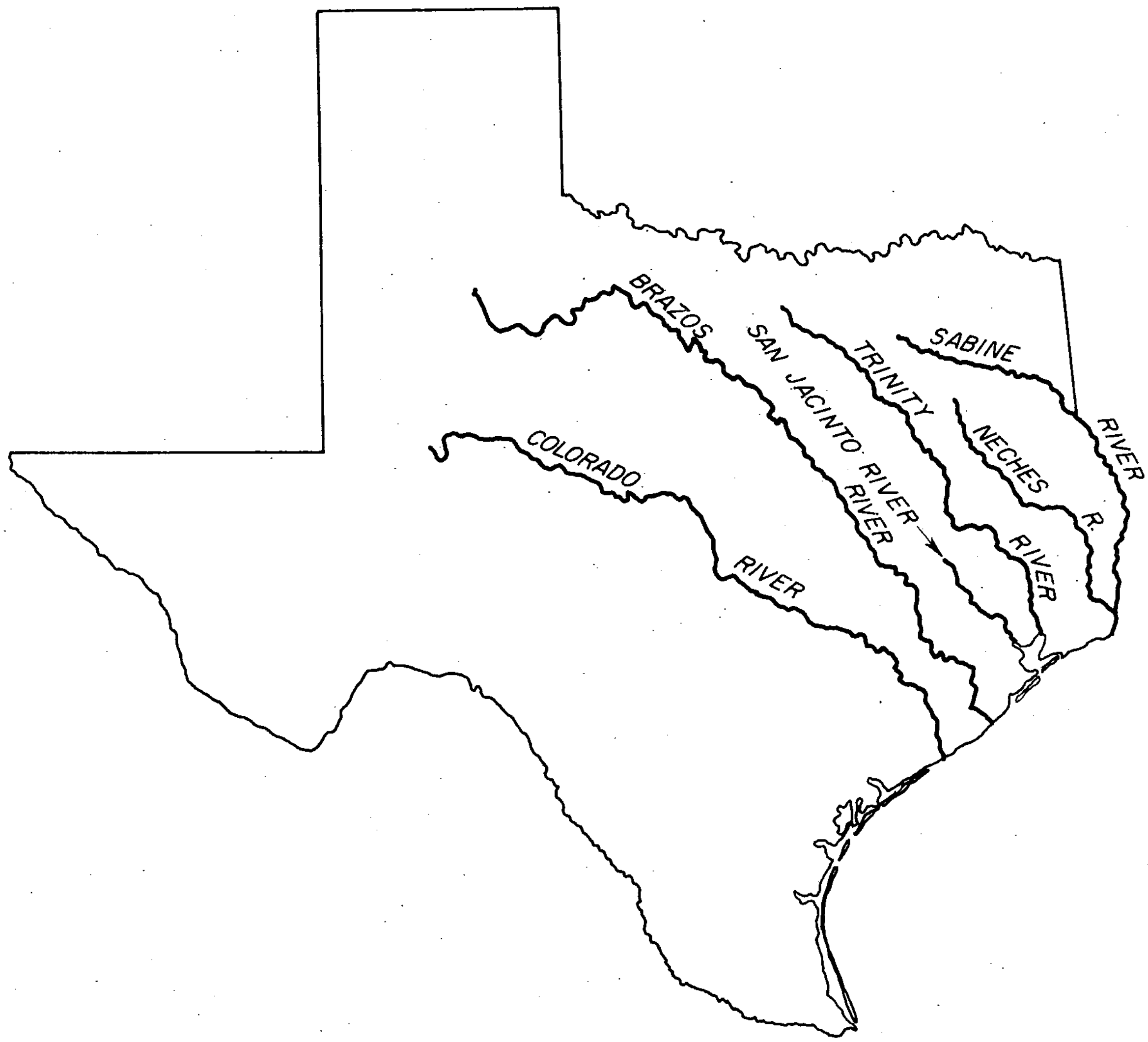
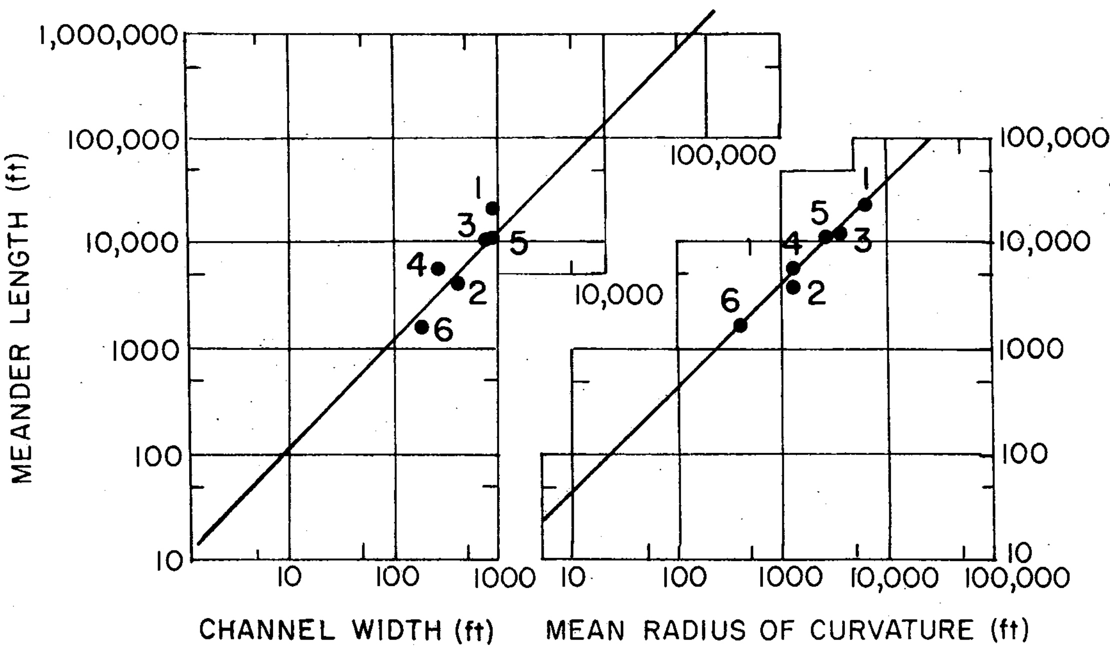


Figure 25. Major rivers flowing through the Gulf Coast of Texas.

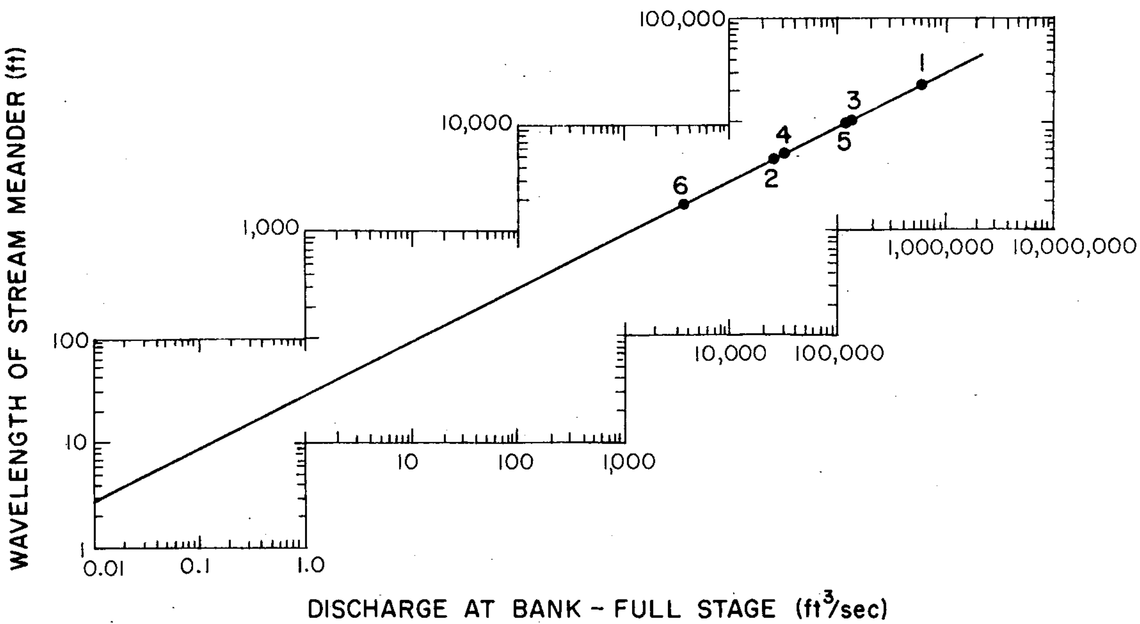
Table 2. Channel Dimensions Measured From Topographic Maps

River	Age of Deposit	Radius of Curvature (ft)	Meander Length (ft)	Channel Width (ft)
Trinity	Pleistocene	6,239	22,251	892
Trinity	Modern	1,496	4,576	352
Sabine	Pleistocene	3,898	11,918	709
Sabine	Modern	1,531	5,333	291
Neches	Pleistocene	3,262	11,433	884
Neches	Modern	422	1,725	211



	RIVER	AGE OF DEPOSIT	RADIUS OF CURVATURE (ft)	MEANDER LENGTH (ft)	CHANNEL WIDTH (ft)
1	TRINITY	PLEISTOCENE	6,239	22,251	892
2	TRINITY	RECENT	1,496	4,576	352
3	SABINE	PLEISTOCENE	3,898	11,918	709
4	SABINE	RECENT	1,531	5,333	291
5	NECHES	PLEISTOCENE	3,262	1,433	884
6	NECHES	RECENT	422	1,725	211

Figure 26. Graph by Leopold and Wolman (1960) with data measured from topographic maps.



	RIVER	AGE OF DEPOSIT	RADIUS OF CURVATURE (ft)	MEANDER LENGTH (ft)	CHANNEL WIDTH (ft)
1	TRINITY	PLEISTOCENE	6,239	22,251	892
2	TRINITY	RECENT	1,496	4,576	352
3	SABINE	PLEISTOCENE	3,898	11,918	709
4	SABINE	RECENT	1,531	5,333	291
5	NECHES	PLEISTOCENE	3,262	1,433	884
6	NECHES	RECENT	422	1,725	211

Figure 27. Graph by Schumm (1977) with data measured from topographic maps.

theoretical capacity to produce gravels, further exploration can take place.

Selection of High Potential Target Areas

There are two basic methods for selecting high potential target areas that will be discussed in this section: 1) point bar exploration and 2) applied quantitative river morphology exploration. The point bar approach relies on using visual and photographic techniques to locate the surface expressions of these deposits. The second approach must rely on measured physical characteristics on the modern river channels to characterize the type of material over which it is flowing.

Point Bar Exploration. This exploration technique will begin with identification of specific point bar deposits in the river terraces which are considered to be potential sources of gravel. The general outline of point bar deposits can be detected on topographic maps (Figure 28) as well as black and white aerial photos (Figure 29). Aerial photos of many river systems may be obtained from the United States Department of Agriculture. When target areas have been selected, field reconnaissance will be necessary to establish ownership and access.

Applied River Geometry Exploration. The objective of this approach is to locate buried valley fill, tributary influx, nickpoint and growth fault deposits that have been buried by fine grained sediments. As a river erodes downward into coarse grained materials, the hydraulic conditions change since the river soon becomes unable to erode the coarse material further. As a result, the river will change in physical character. Sometimes these changes show up as obvious visual changes

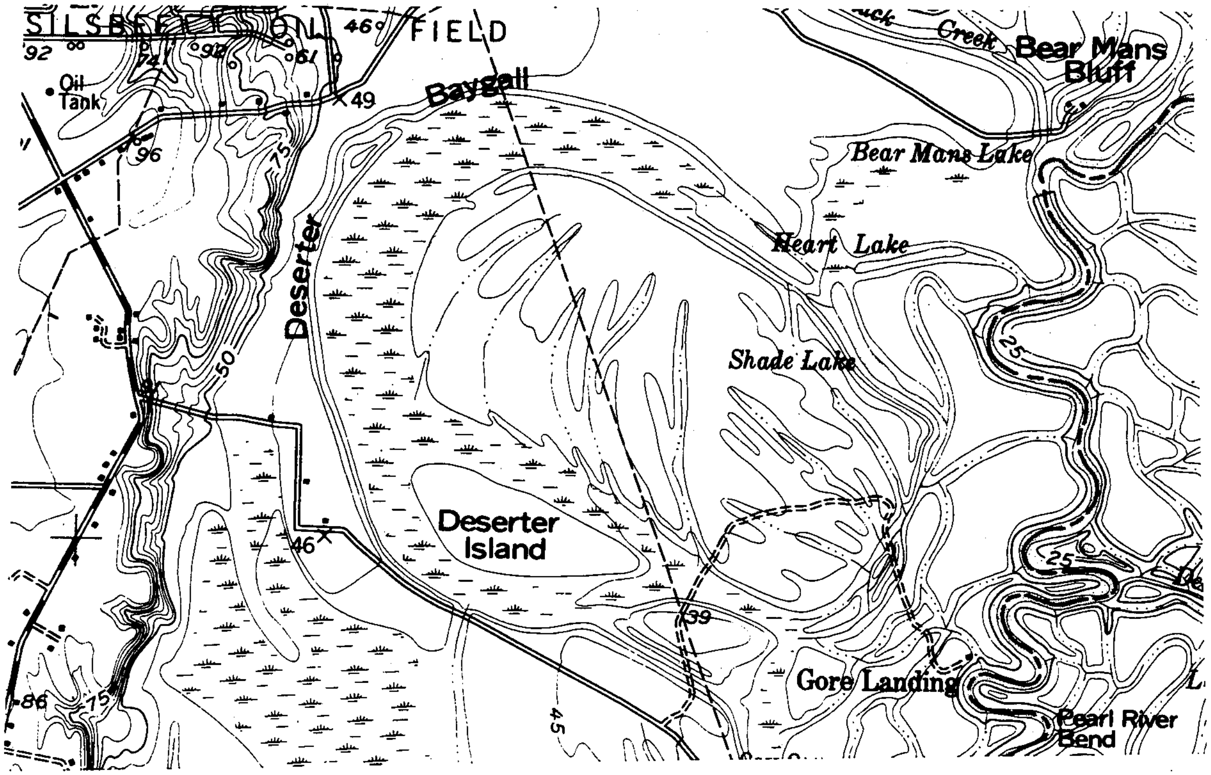


Figure 28. Topographic map of an ancient point-bar deposit along the Neches River. (Map based on the Silsbee, Texas, 7 1/2 minute quadrangle map, C.I. = 5 feet.)

Figure 29. Black and white aerial photograph of the same point-bar shown in Figure 28.

such as becoming wildly meandering while adjacent sections remain relatively straight, or by developing falls and rapids when adjacent stretches appear as slow moving pools. At other times, as often is the case with Texas Gulf Coast rivers, the changes are too subtle to pick out by a visual inspection. Changes must be detected by careful measurement of river dimensions. Subsurface gravel deposits can affect gradient, channel width and sinuosity (degree of meandering or linearity of channel).

Channel gradients become steeper as a river impinges on a deposit that contains coarser gravel material than the present river is able to transport. Figure 30 shows how a channel will increase its gradient by removing erodable material downstream from the gravel creating a high point in the channel where the gravel exists. The river in the figure originally had a uniform gradient along its entire length. After intersecting the gravel deposit, the gradient increased significantly until the entire deposit was removed. The river will also maintain a characteristically high sinuosity. This situation occurs often in Gulf Coast rivers where small rivers are found flowing over alluvium deposited by much larger rivers of the Pleistocene glacial periods.

High potential zones can be targeted by measuring river gradient and sinuosity from topographic maps. River gradient is determined by measuring the horizontal distance between each elevation contour. Sinuosity is calculated by dividing the distance measured along a river channel by the length of valley in which the river is flowing. These measurements are compared by plotting sinuosity vs. distance and gradient vs. distance on the same graph. Figure 31 shows just such a plot for a

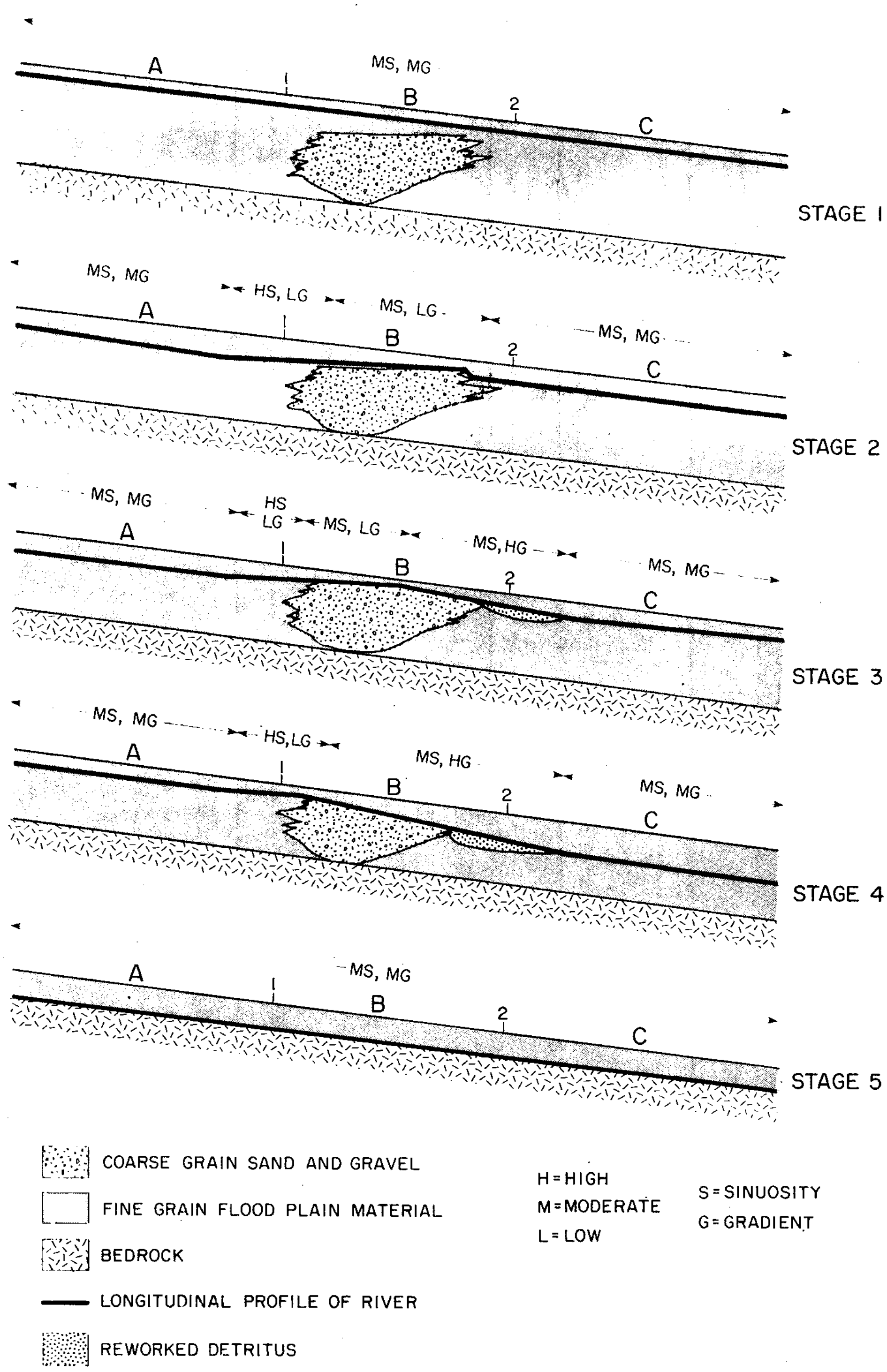


Figure 30. Sequential changes in channel gradient as a river impinges on a buried gravel deposit.

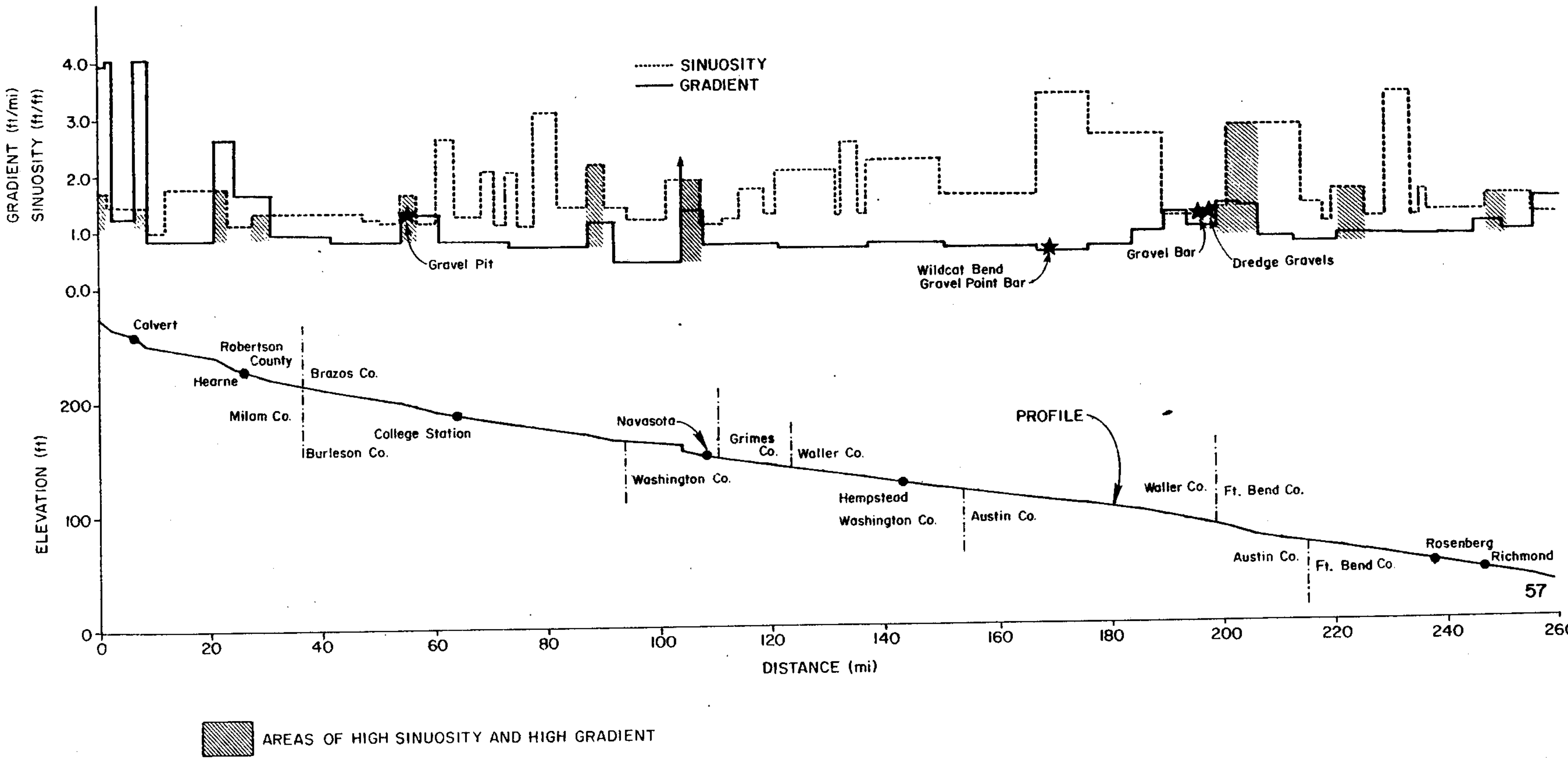


Figure 31. Graphical plot of river gradient vs river distance, river sinuosity vs river distance and the longitudinal profile for the Brazos River.

section of the Brazos River. High potential sites are those that exhibit both high sinuosity and high gradient.

Electrical Resistivity Evaluation

Once a high potential prospect has been located, electrical resistivity methods may be used to define the depth and lateral distribution of a suspected aggregate producing horizon. Different earth materials may be distinguished from each other to some extent by evaluating the changes in current potential drop across a known ground, surface distance to determine resistivity variations with depth as well as lateral extent. Resistivity values for gravel are generally much higher than values for clay and sand mixtures. This method is especially effective in the near subsurface and therefore is highly practical for gravel exploration.

Theory. The electrical resistivity survey method relies on the fact that there are variations in conductivity of subsurface materials, some of which are more resistant than others to electrical current passing through them. Resistivity is basically the resistance (ohms) between opposing faces of a unit cube of a given material and is therefore a fundamental property of the material. Resistivity units are in ohms per length - i.e. ohm/ft or ohm/meter. When an electrical current is applied to the ground, the resistivity differences cause the current flow paths to be refracted across boundaries, thereby changing the voltage potential gradient across a volume of earth material. The magnitude of voltage potential changes measured at the ground surface is governed by the size, location, and resistivity of subsurface bodies or layers. In the case of a high resistivity gravel deposit overlain by lower resistivity material like clay (Figure 32), the current flow lines will be deflected away from the gravel and concentrated in the upper medium, thereby increasing the current recorded at the potential electrodes and the apparent resistivity. If the layers were reversed, more current would flow in the lower layer and a greater potential drop would be recorded (11,19).

Surface resistivity measurements are made by pushing four electrodes into the ground at predetermined intervals along a survey line. Current (I) is applied to the ground through the two outer electrodes (Figure 33). The volume of material that the current spreads into, and therefore the depth of penetration, is proportional to the electrode spacing. Many factors may affect depth of penetration but an accepted average is approximately 20 to 30 percent of the widest reliable spacing of the two current electrodes. A potential gradient develops between each current electrode and both potential electrodes. Current drop is measured at the potential electrodes. This measurement is actually an apparent resistivity because it is a weighted average of all of the resistivities through which the current passes. If the material were completely homogeneous the measurement would be true resistivity (11,19, 20).

With the exception of metallic sulphides and rocks containing clays, electrical conduction in rocks occurs basically through the water occupying the pore spaces. Pore water contains dissolved salts which act as electrolytic conductors. Most mineral grains are non-conductors. Resistivity is related to the type of electrolyte present in the water as well as effective porosity and degree of saturation. Generally,

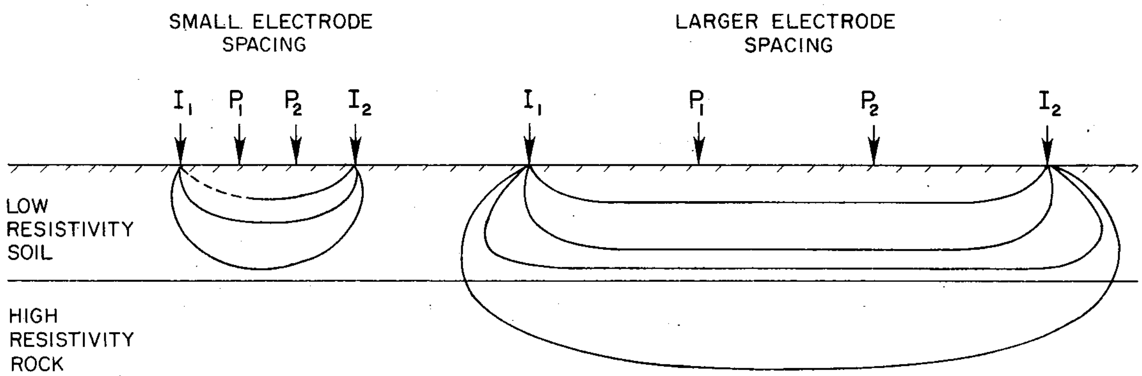


Figure 32. Schematic diagram showing how electrical current is concentrated in low resistivity earth materials and is deflected away from high resistivity materials.

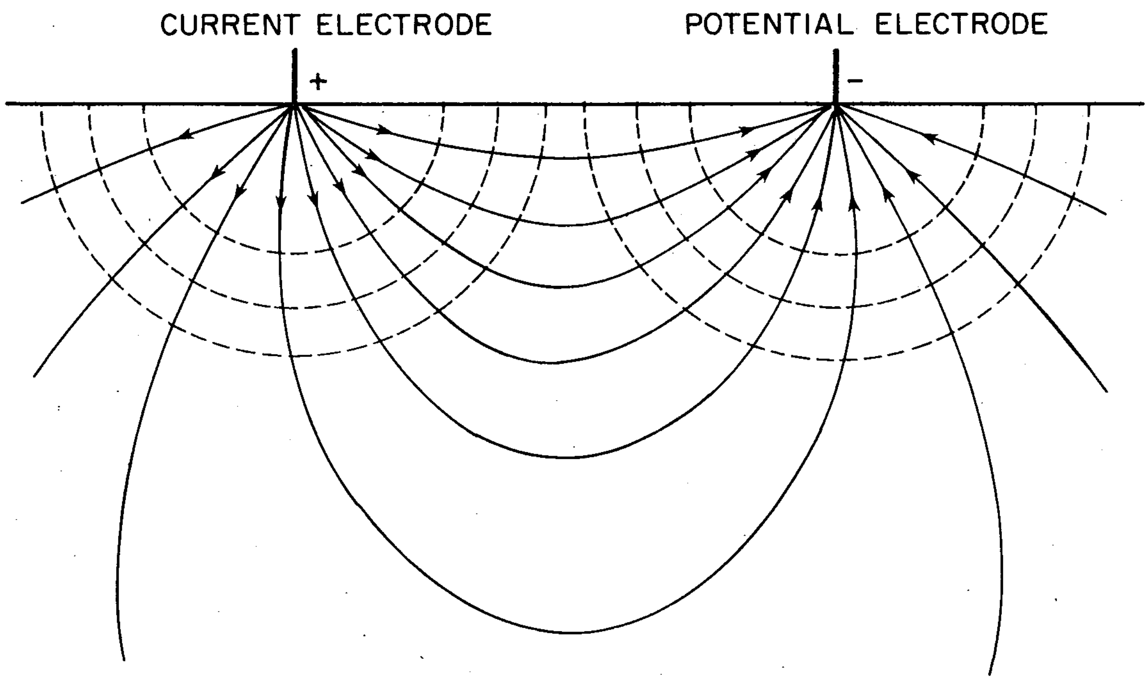


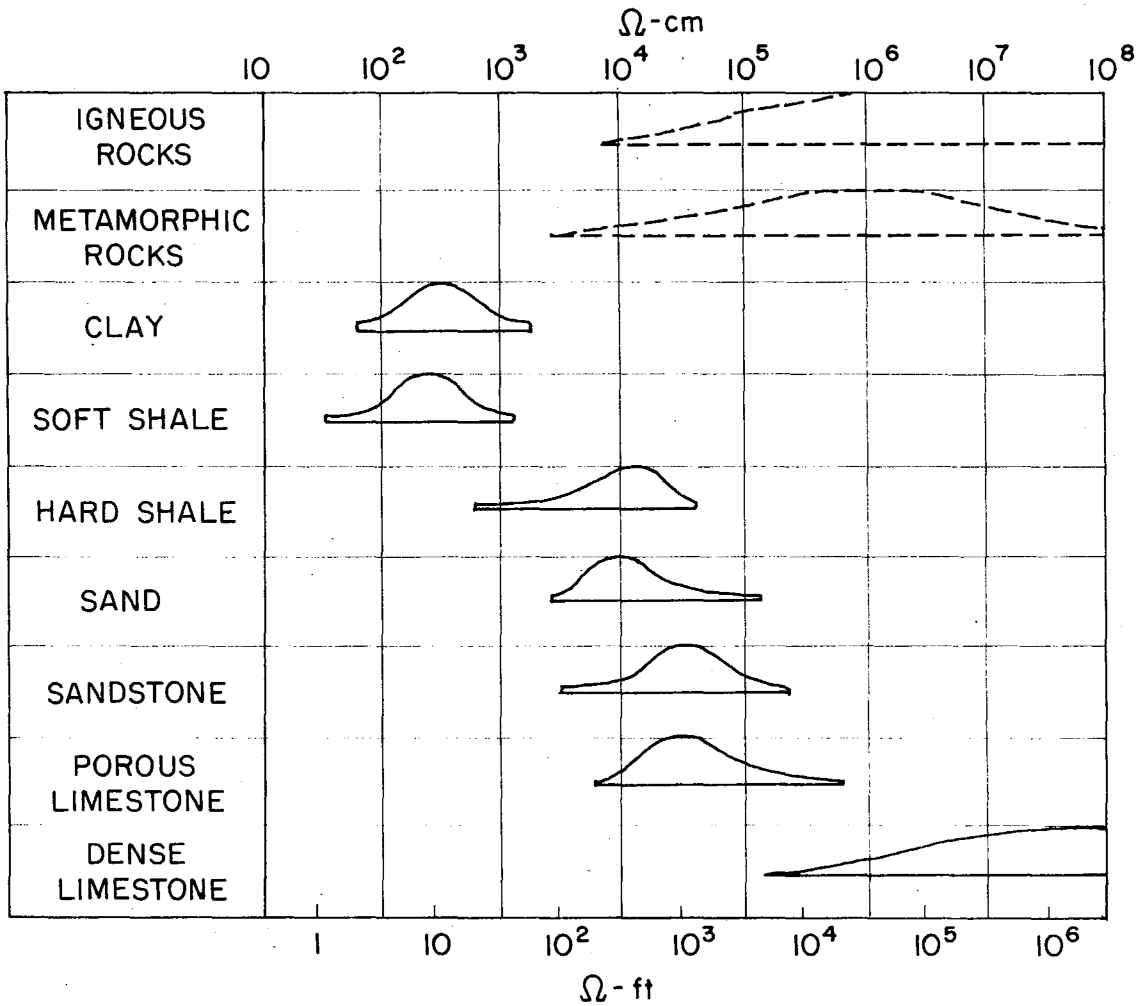
Figure 33. Current flows out radially from the electrodes.

resistivity decreases as water content and/or salinity of the formation water increases. If gravel is dry or saturated with clean, low salinity water, it should have a fairly high resistivity. If it contains clay or soil, the resistivity will be reduced (11, 19).

Although formation resistivities may vary widely, even within the same deposit, it is possible to make lithological generalizations. Resisitvity generally increases in the following order: clay, sand and gravel, limestone, and crystalline rocks. Table 3 gives relative resistivity ranges for common rocks.

Technique. Electrical resistivity evaluation of shallow gravel deposits will require a resistivity transmitter/receiver, reels with cable, electrodes, and cloth or fiberglass measuring tapes. The transmitter and receiver may be a single unit or separate units. First, the desired center of the survey line is chosen and the ends of two measuring tapes are anchored there. Generally, this is where the resistivity unit is also set. The tapes are laid out in opposite directions along the line and the electrodes are placed in the ground at desired spacings along the tapes, two on each side of the center. After the current and potential cables are connected to the unit the cables are carefully unwound and attached to the respective electrodes. Current is provided by a 90 to 120 volt battery to the current electrodes. The current flowing along the surface is picked up by the inner electrodes and the potential gradient is measured by a voltmeter. This is recorded on the reciever as a digital dial reading at a certain scale setting. Multiplication of the dial reading times the scale setting gives the quantity $2\pi V/I$, or resistance in ohms. This quantity times the electrode

Table 3. Relative Resistivity Ranges for Common Rocks



spacing ("A" spacing) provides a measure of apparent resistivity. Explicit field operation information is included with each instrument.

Several versions of earth resistivity systems (such as Bison Instruments Model 2350 that is shown in Figure 34 or Soiltest Model R-90) will be suitable for gravel exploration. The single unit transmitter/reciever systems are small, highly portable, and easily operated by a one or two man field crew. These units are very good for shallow investigations - usually 100 ft or less. For deeper and more sensitive measurements, there are resistivity systems with the signal enhancement feature available (such as Bison Instrument's Model 1570C). Signal enhancement increases instrument sensitivity by adding together many small signals over a period of time to produce a much higher quality signal. The signal enhancement systems often have separate transmitter and receiver units connected by a synchronizer cable; multiple receiver units allow increased data gathering capability. Resistivity systems with the signal enhancement feature are smaller and lighter and require less power to produce the same results as regular resistivity systems.

The most commonly used and most easily interpreted electrode arrangement is called the "Wenner" arrangement. In the Wenner configuration, the four electrodes are placed at equal A-spacings along a line with the current electrodes at the outer ends (Figure 35). From the center of the line the potential electrodes are always at a distance of A/2 and the current electrodes are always at 3A/2. A-spacing will depend upon the type of survey, the desired depth of penetration and the desired sensitivity. Small electrode spacing is advantageous for detecting small, shallow structures or inhomogeneities; however, spacings

Figure 34. Photograph of electrical resistivity unit.

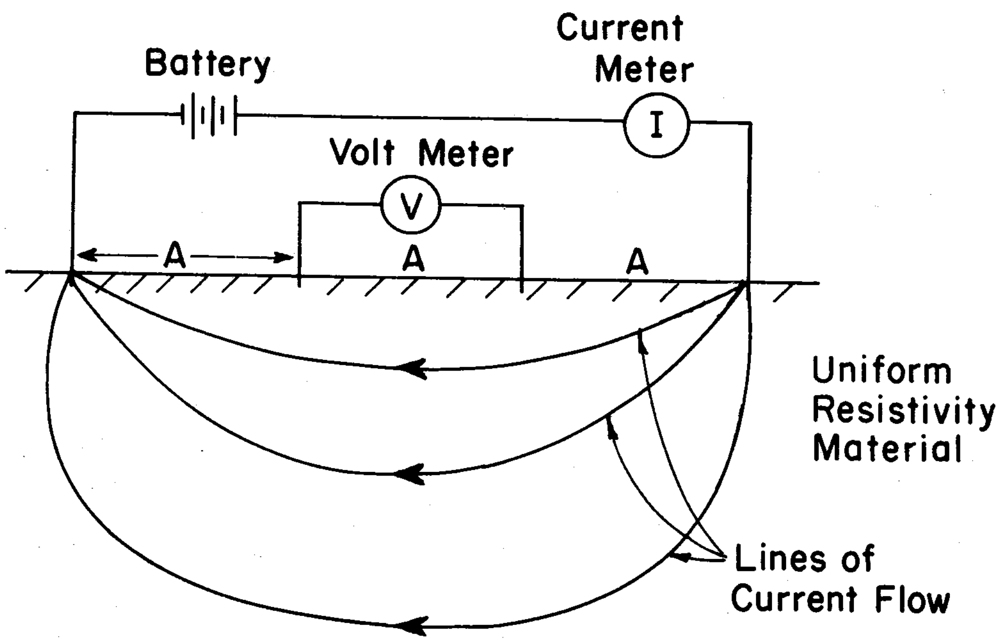


Figure 35. Schematic diagram of an earth resistivity meter system set up in a Wenner array.

smaller than 2 to 3 ft may cause interference in the readings due to the proximity of current and potential electrodes. Detection of larger and deeper structures will require larger electrode spacings (Figure 36). A-spacing should reach approximately three times the desired depth of investigation (11, 19, 21).

There are two basic types of electrical resistivity surveys - profiling and sounding. For a resistivity profile, the A-spacing is held constant for every reading and the whole survey line is moved over an area in a series of parallel and perpendicular stations (Figure 37). Profiling data is recorded on a graph of apparent resistivity versus distance (Figure 38). Depth of penetration will essentially be constant, therefore this type of survey will provide information about the location and lateral boundaries of a suspected gravel deposit. Running resistivity profiles on a grid-type system provides data which can be contoured to produce an equal resistivity contour map (Figure 39) (19, 21).

For a resistivity sounding, the center of the survey line remains in the same position while the electrode spacing is increased by increments for each resistivity reading (Figure 40). The A-spacing between electrodes is always equal and the electrode spread is symmetrical about the center. Depth of investigation increases with each increase in electrode spacing, allowing delineation of vertical resistivity changes such as depth to the water table and depth and thickness of a high resistivity anomaly. Sounding data is plotted on a graph of electrode spacing versus apparent resistivity (Figure 41). A potential source of error in the interpretation of sounding data is the confusion of lateral resistivity variations with vertical variations. Running two

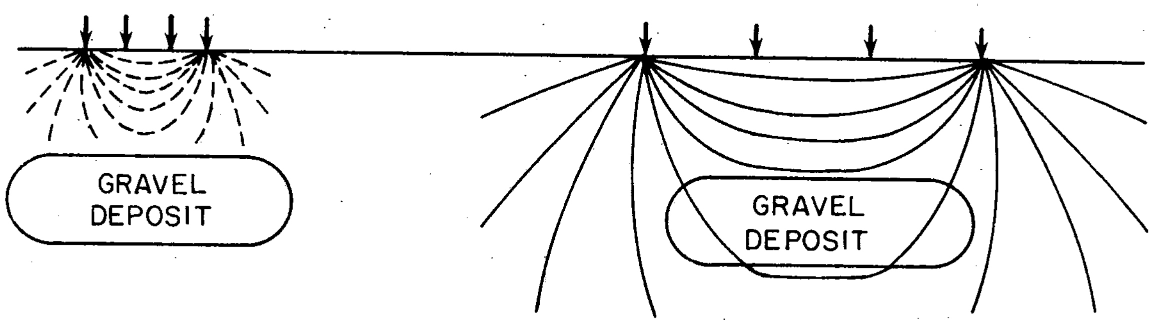
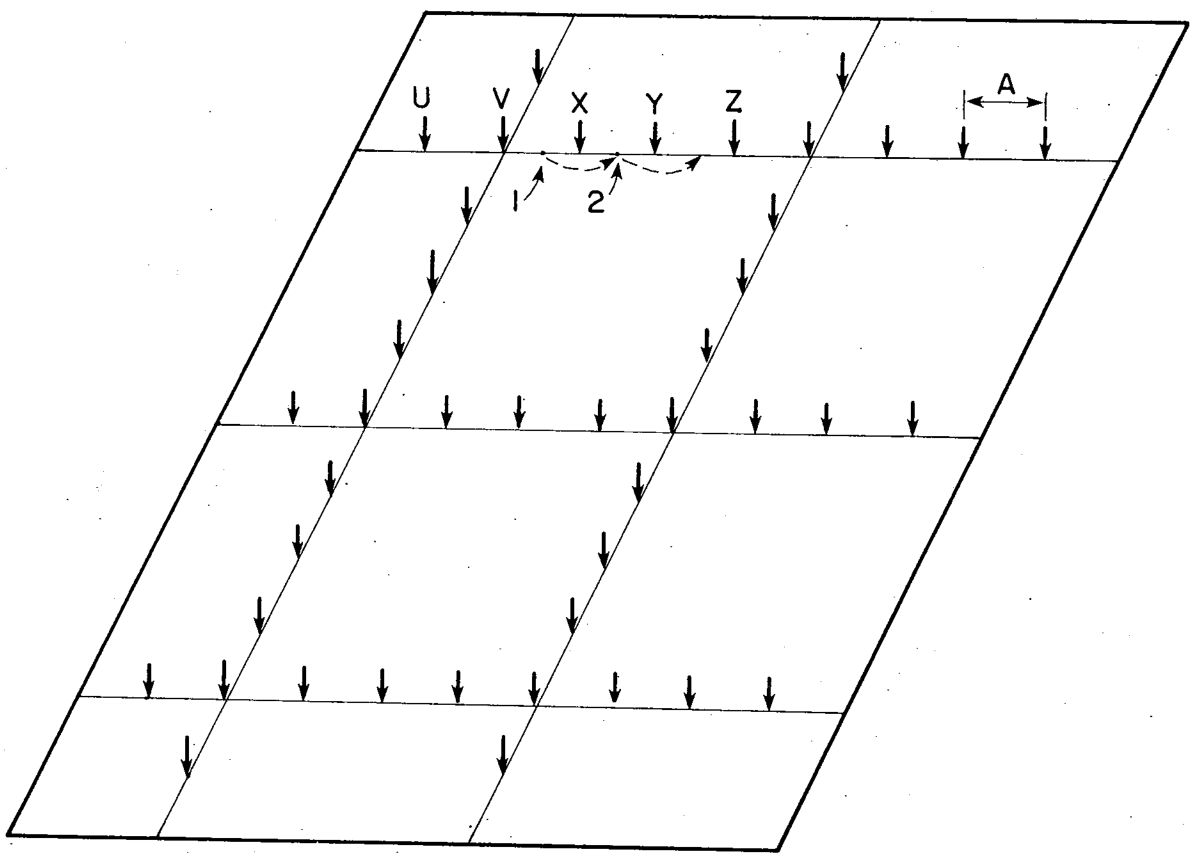


Figure 36. Schematic diagram demonstrating that larger electrode spacings are necessary to detect deeper deposits.



A = "A" SPACING

↓ = ELECTRODE POSITION

Figure 37. Schematic layout of an electrical resistivity profile. The survey would begin at a station such as #1. The instrument would rest at station #1 and the four electrodes would be at U, V, X and Y. After recording the reading the instrument is moved to station #2 and the electrodes are placed at V, X, Y and Z. This process is continued until the entire area is covered. The "A" spacing is kept constant throughout the survey.

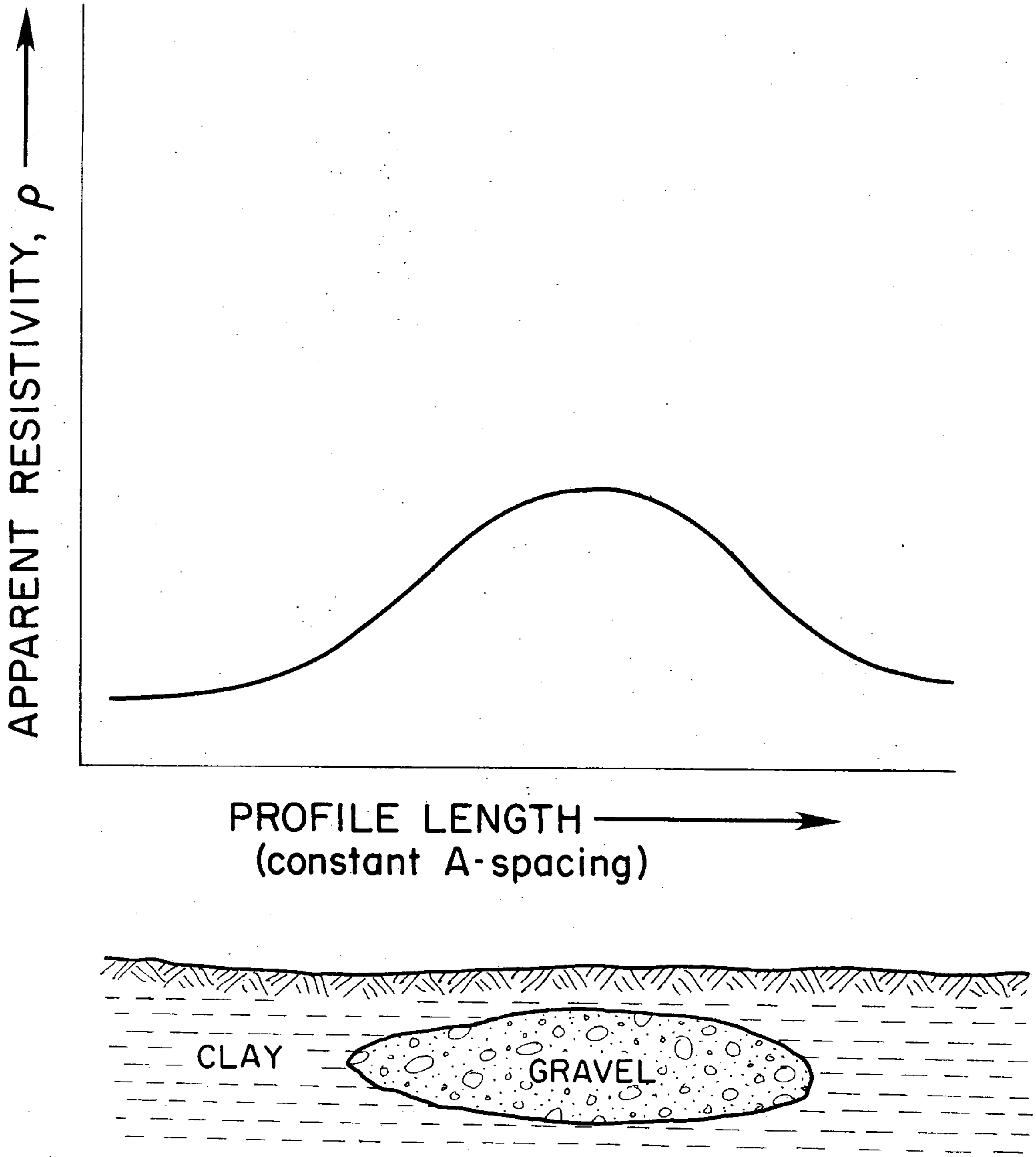


Figure 38. Schematic representation of plotted data from a profile over a gravel deposit encased in clay.

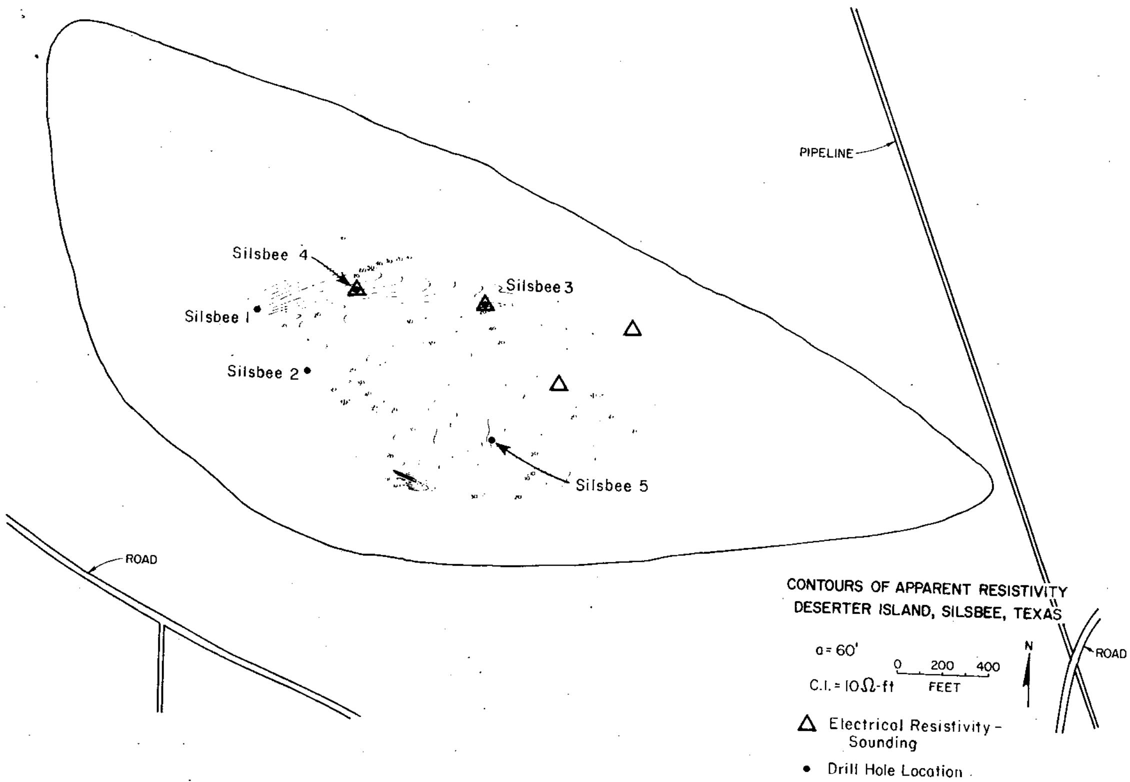


Figure 39. Contour map of apparent resistivity for Deserter Island, Silsbee, Texas.

ELECTRICAL RESISTIVITY SOUNDING

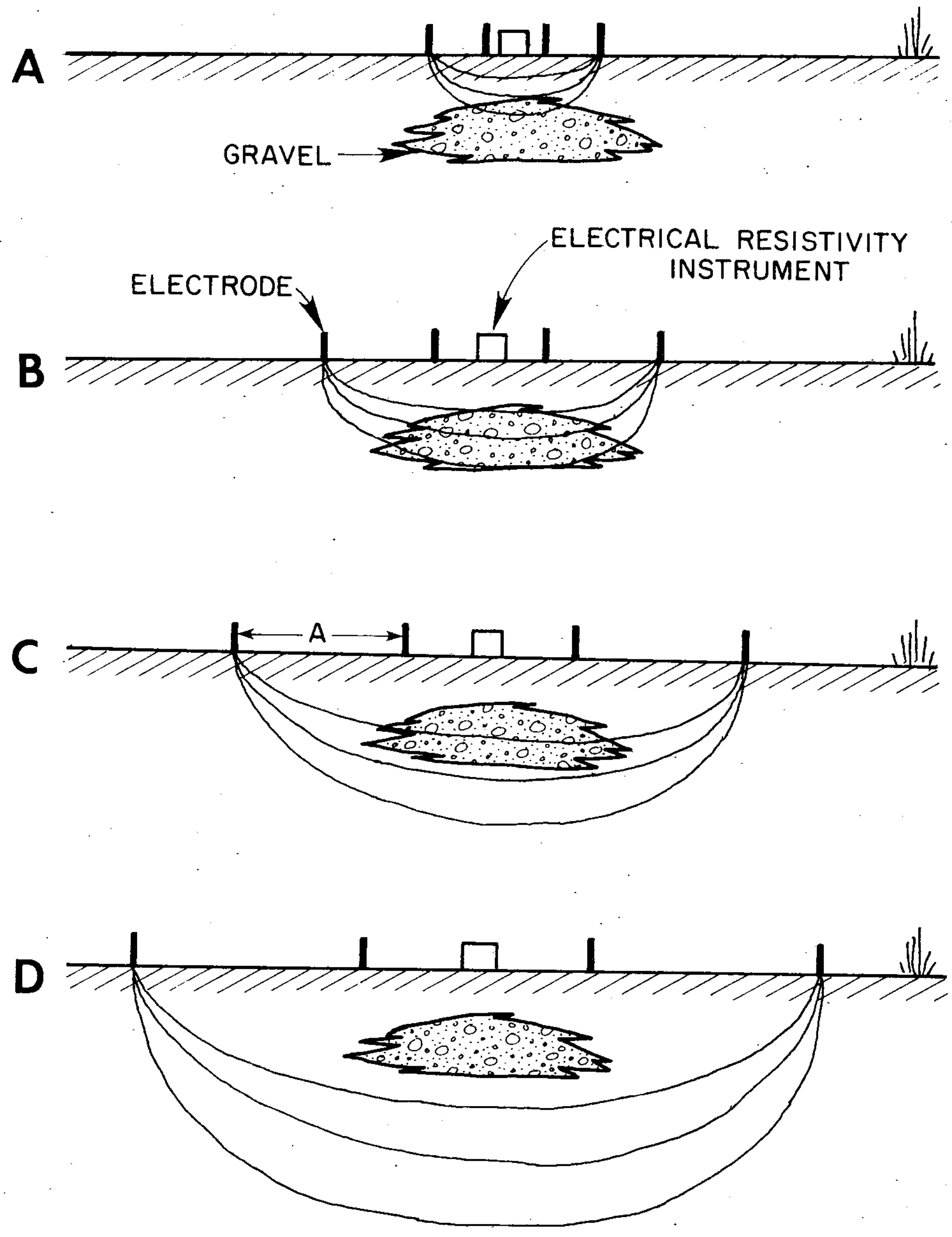


Figure 40. Schematic diagram showing the progressive increases in "A" spacing necessary to gain a knowledge of changes in earth materials with depth.

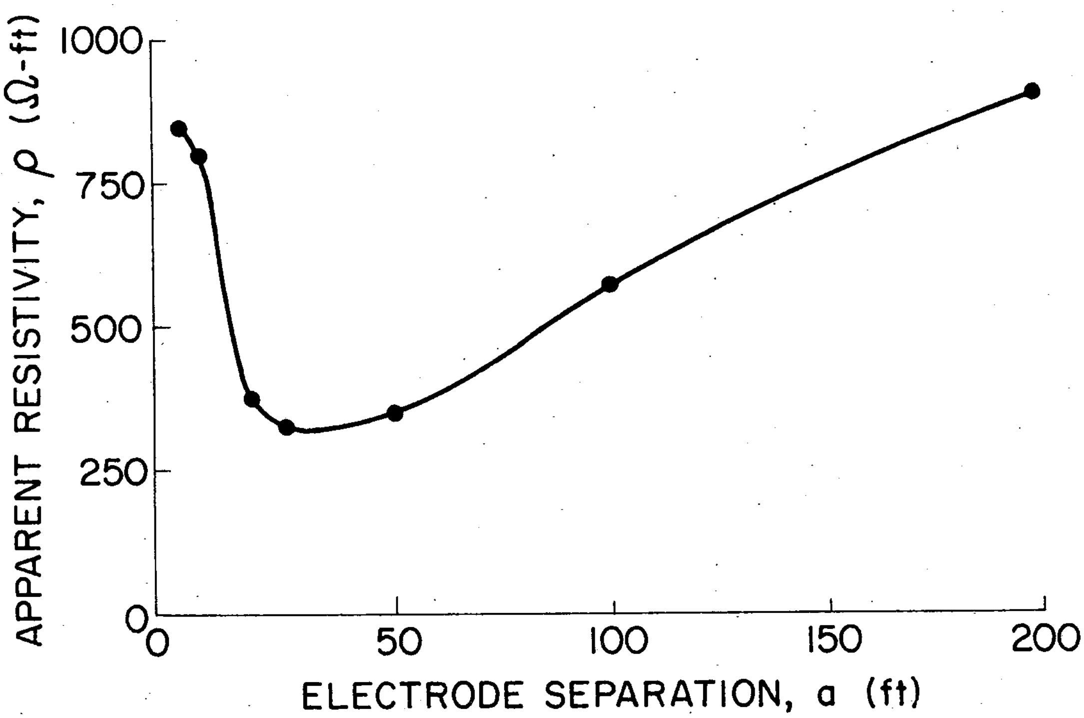


Figure 41. Plot of sounding data on a graph of electrode spacing vs apparent resistivity.

perpendicular sounding surveys from the same center will aid in data interpretation. If the two data graphs are the same then there is probably some sort of vertical variation; if they are different, the variation is probably lateral (11, 19, 21).

A very important aspect in applying resistivity methods to gravel prospecting is tying resistivity survey data to real subsurface data. Real data may be borehole information, general geologic information of the area, a nearby quarry, or resistivity data over known gravel deposits in the area. This will facilitate qualitative interpretation.

Interpretation. Electrical data for point bar gravel exploration lends itself quite readily to qualitative interpretation because the gravel is shallow and has a much higher resistivity than the surrounding materials and the subsurface structure is generally close to a simple horizontal layer configuration. Both profiling and sounding data curves as well as resistivity contour maps resulting from the above conditions are fairly easily interpreted by visual examination. Since there is reason to believe that gravel is present before the survey was run, interpretation involves searching for high resistivity values relative to the other materials present. It may be difficult to distinguish between clean sand and gravel deposits from resistivity data, however borehole data or other information should be used to distinguish between the two. Quantitative methods are also available for interpretive uses of the same data.

Profiling data is plotted on a graph with apparent resistivity as the ordinate and the location of the center of the electrode spread as the abscissa. As the electrode spread is moved across the higher resistivity material, the change in the curve from low to higher resistivity readings is generally smooth. Figure 42A shows profile data across a shallow, relatively thin gravel deposit. A small A-spacing (relative to the depth of the deposit) is able to record the change to a higher resistivity material because the current is confined nearer the surface where it is more sensitive to the gravel. A wider A-spacing would be affected to lesser degree. A shallow, thick gravel deposit (Figure 42B) will produce similar curves at large and small A-spacings because of the size of the body even at shallow depths. For a deep, thick gravel deposit (Figure 42C), the curve produced at a larger A-spacing is more informative because at smaller A-spacings the gravel body has little effect on the readings. These curves provide general information on the location and shape of a deposit and to some extent an indication of depth. Verification with drill hole data will improve the results considerably.

Profiling data which has been gathered along parallel lines over an area can be plotted on a map and contoured. The resistivity reading for each survey is plotted at the position of the center of the electrode spread on the map. Lines of equal resistivity are then drawn from the data. This process provides an idea of the lateral boundaries and subsurface configuration of the body, and may be used to set up a boring and sampling program (11, 19, 21).

Data from electrical resistivity soundings is recorded with apparent resisitvity as the ordinate and electrode spacing as the abscissa. Increasing electrode separation generally corresponds to increasing depth of investigation, but now with a constant relationship or proportionality.

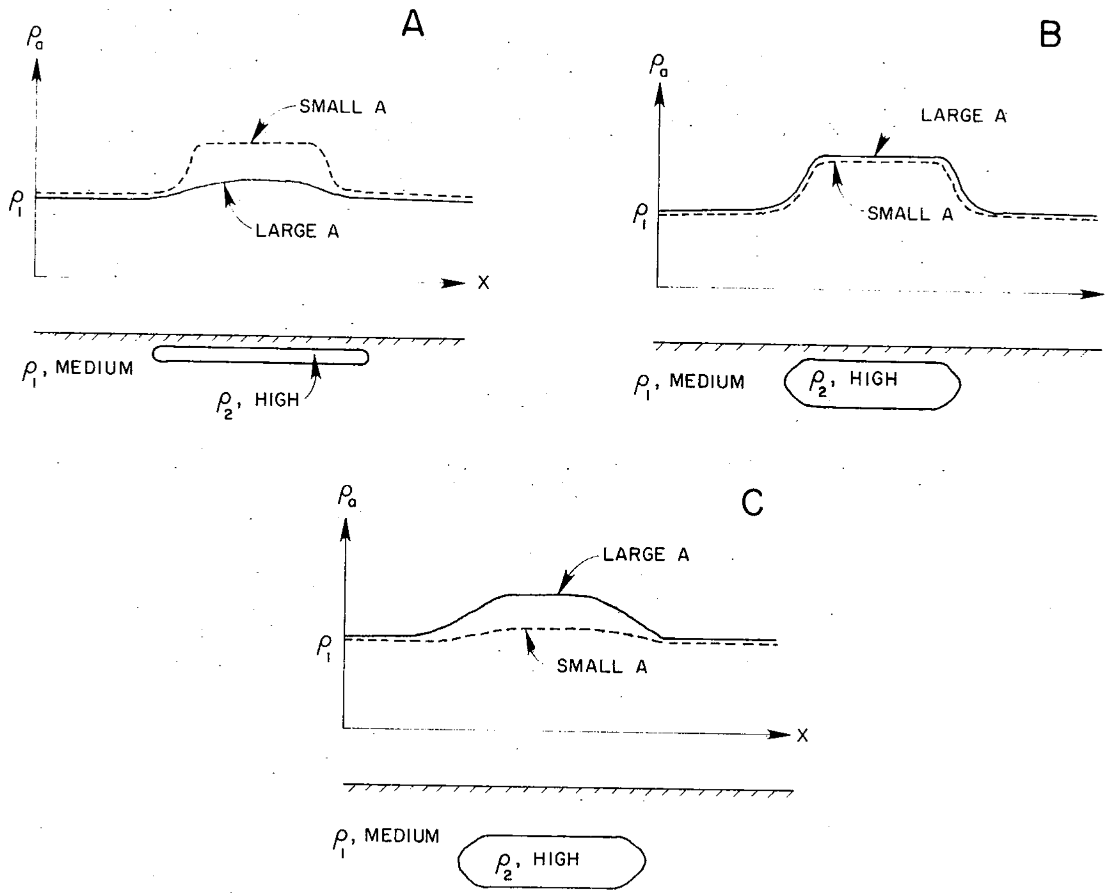


Figure 42. Schematic plots of resistivity versus distance for profiles run over gravel deposits at different depths.

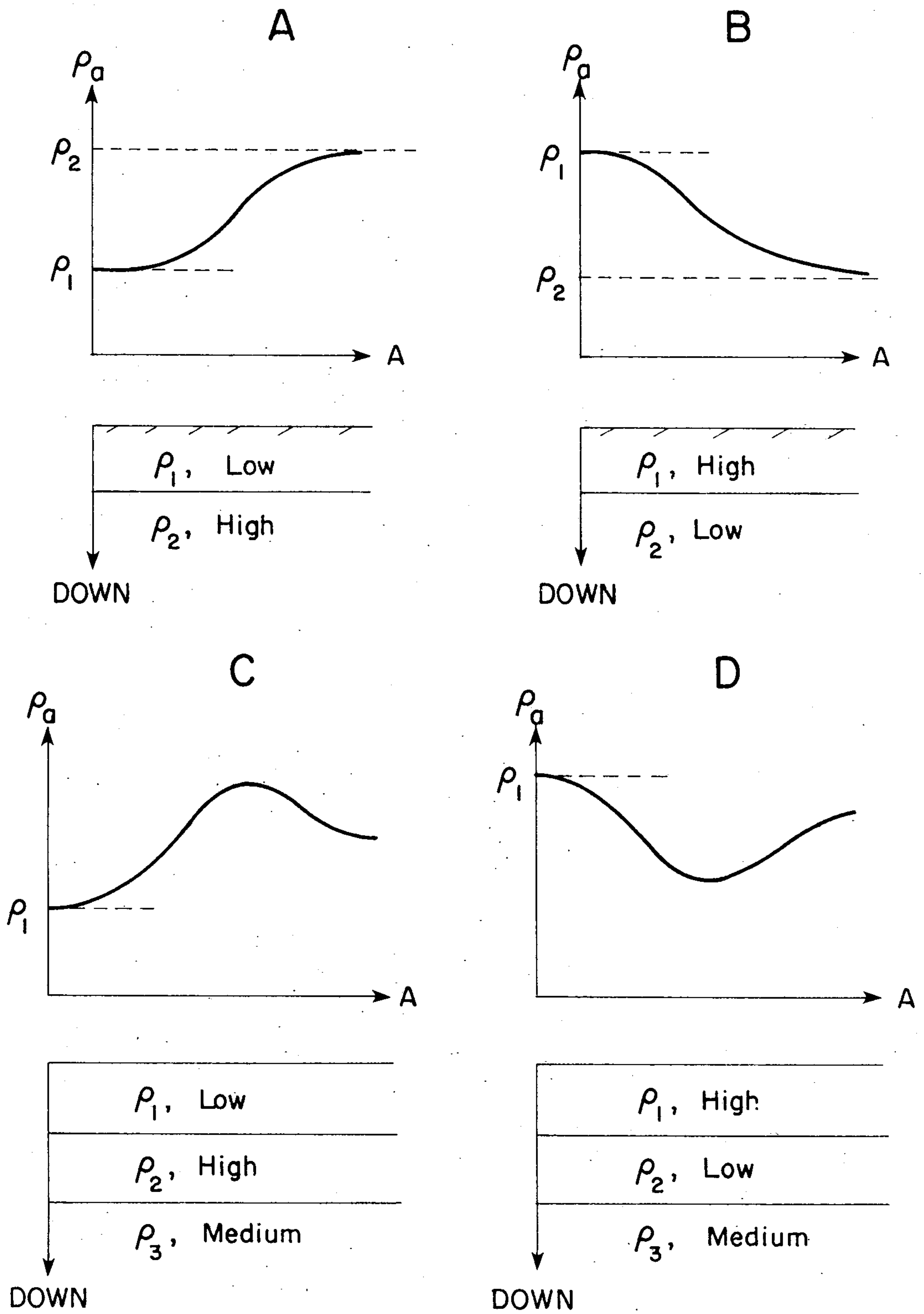


Figure 43. Schematic representation of soundings over various layered subsurface structures.

Therefore, sounding curves are useful when they are interpreted qualitatively for point bar exploration. Sounding data records vertical layer changes with smooth changes in the resistivity curve. At small A-spacings the recorded resistivity is approximately equal to the true near surface resistivity; at greater A-spacings the recorded apparent resisitvities produce a gradual change in the curve. For a low resistivity layer overlying a high resistivity layer (such as soil over gravel), the curve may resemble figure 43A. Figure 43B represents a decrease in resistivity with depth, i.e. gravel over clay. Figures 43C and 43D are more complicated curves for several layers of differing resistivity.

Quantitative methods are available for interpreting resistivity soundings. These methods are designed to determine depths and thickness or horizons by matching the sounding curves to one of a series of curves developed from actual two and three layer cases. The most complete set of curves available were published by Orellana and Mooney (22). Other, less extensive methods, such as Tagg's (11), Barnes Layer and Moore Cumulative Method (19) are available. All these methods rely on curves or techniques developed on real geologic examples. Unfortunately, every geological situation is unique, therefore these interpretations are subject to appreciable error. The use of these methods also requires a great deal of time and understanding of the principles. Since these deposits will be evaluated with a drill rig anyway, it is more efficient and effective to use the qualitative methods.

Sampling

After a prospect has been defined using electrical resisitivity techniques, it should be sampled. Sampling should be accomplished with an auger rig. This type of rig is capable of retrieving all grain sizes that it encounters. It is important to know the maximum particle sizes, percent sand and gravel in each sample, and the composition of the material sampled.

HIGH GRAVELS

High gravels (deposits that are found on hilltops) are fluvial in origin and later act as an erosion resistant armour that causes the interchannel areas to be preferentially eroded. The result is a series of gravel covered hills between eroded valleys that are commonly found associated with the Pleistocene Willis Formation in the southeast Texas area.

GEOLOGY OF THE WILLIS FORMATION

The Willis Formation is a fluvially deposited formation that crops out in Texas in a twenty-five to thirty mile wide band paralleling the Texas Gulf Coast (Figure 44). The Willis rests unconformably on the Miocene Fleming Formation (23). The Fleming Formation has been completely removed, allowing the Willis to rest on the Catahoula in some areas of east Texas (24). The Willis Formation is characterized by cross bedded clays, silts, sands, and gravels, with a color and composition that varies both vertically and laterally throughout the formation. The color varies from brick red to mottled red and white near the type section in Montgomery and San Jacinto Counties from yellow to brownish-yellow in Polk, Tyler, Jasper, and Newton Counties (25). The color is basically determined by the composition, which varies depending on the river system that deposited it. The bulk of the material in east Texas was produced from the iron-rich Claiborne Group (25). The red color comes from hematite and the yellow tints are produced by limonite. Iron commonly acts as cement and matrix material, but in some areas, it will produce iron nodules that

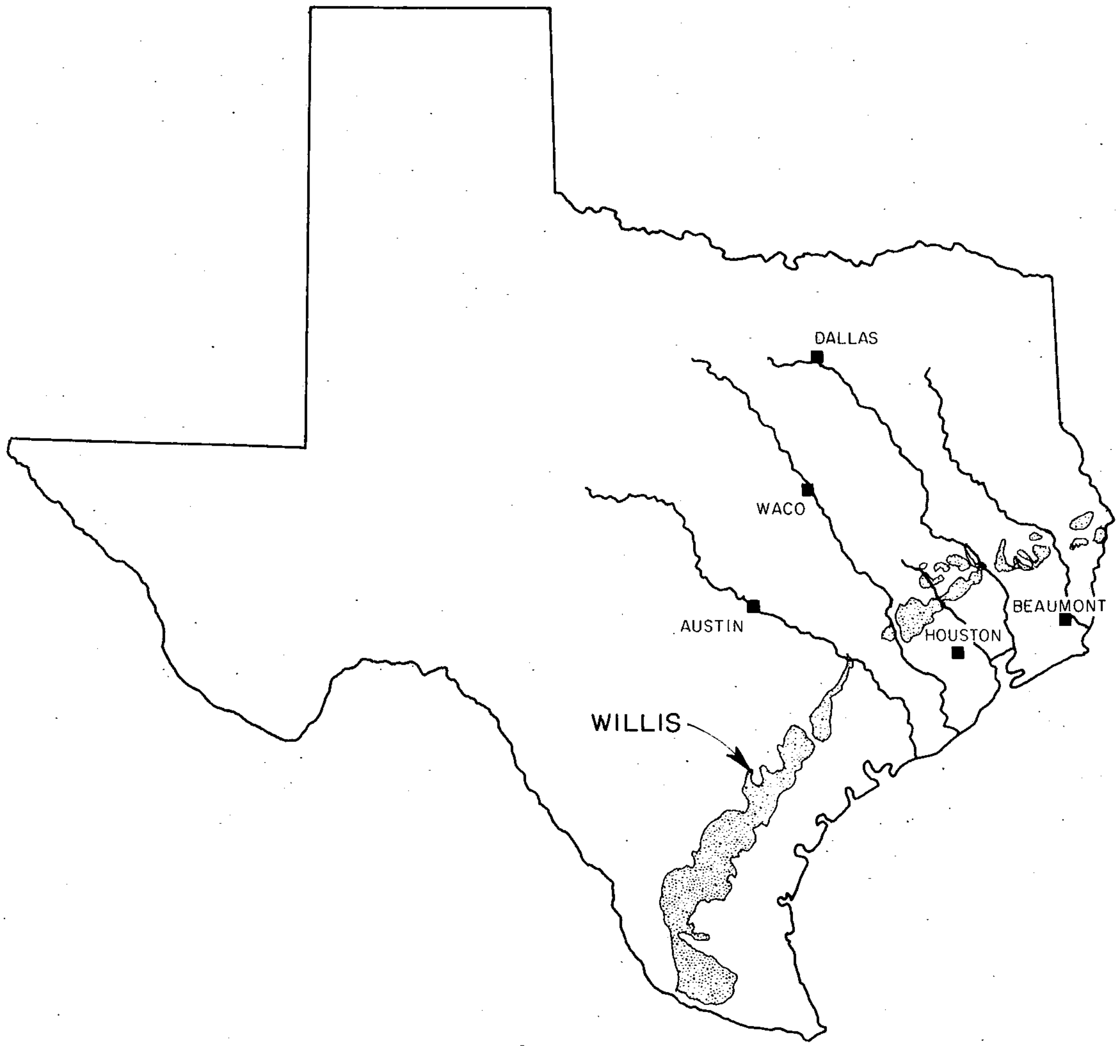


Figure 44. Outcrop belt of the Willis Formation.

commonly range in size from one-eighth to one-half inch. Iron nodules have been used locally as road material.

The gravel is composed of chert and quartz pebbles with a large percentage of limonite nodules. These pebbles are usually less than one inch in diameter and are characteristically sparsely disseminated in a matrix of finer sand, silt, and clay (Figure 45). These gravels are often concentrated on the surface as lag deposits that are left behind when the finer material is winnowed out by erosion (Figure 46). Willis gravels are often further concentrated in local streams (Figure 47). Lag gravels have been known to exist in deposits ranging from two to five feet thick that cover one to ten acres (25).

EXPLORATION FOR HIGH GRAVELS

Exploration for High Gravel is accomplished using the following steps:

a) Initial location of outcrop area

b) Determination of high potential target areas

c) Location of specific deposits

d) Field reconnaissance and evaluation of deposit

These steps will be discussed in detail below:

Initial Location of Outcrop Area

The first step in the exploration for high gravel is to locate the Willis Formation outcrop on a geologic map. Figure 44 shows the generalized outcrop belt of the Willis Formation. The detailed position of the Willis (labeled Qwl, Qwe, Qy) can be seen on the Beaumont (24),

Figure 45. Gravel sparsely disseminated in a background of finer material, Willis Formation, east Texas.

Figure 46. Gravel concentrated on the surface as a lag deposit after the finer grained material has been removed by erosion, Willis Formation, east Texas.

Figure 47. Gravel concentrated in a local stream, Willis Formation, east Texas.

Palestine (6), Houston (26), Austin (3), Seguin (2) Sheets of the Geologic Atlas of Texas published by the Bureau of Economic Geology.

Determination of High Potential Target Areas

Selection of high potential gravel producing regions within the Willis Formation is based on preliminary field reconnaissance and literature studies. Field reconnaissance and well data show that the gravel concentration and size decreases eastward toward Louisiana. Gravel is mostly concentrated near the base of the formation (on the northern fringes of the outcrop belt).

Additional information that aids in the location of high potential zones, can be obtained from the county Soil Surveys published by the United States Department of Agriculture, Soil Conservation Service, and Forest Service. Soil Surveys map soil units based on constituents such as gravel and sand. These maps are developed from aerial photographs and field checking programs.

Location of Specific Deposits

Gravel deposits within the Willis Formation can be located by inspecting color infrared (CIR) or black and white aerial photographs of those areas in which gravel is indicated in well logs or that are close to the base of the Willis (i.e. near the northern border of the outcrop belt). Pine trees tend to grow on the well drained gravelly and sandy soils in east Texas. Where pine forests appear lateral to poorly drained soils, the pine forests show up as dark tones and the swampy vegetation shows up as lighter tones (Figure 48). The pine trees that are growing on deposits of gravel and ironstone are not as healthy as

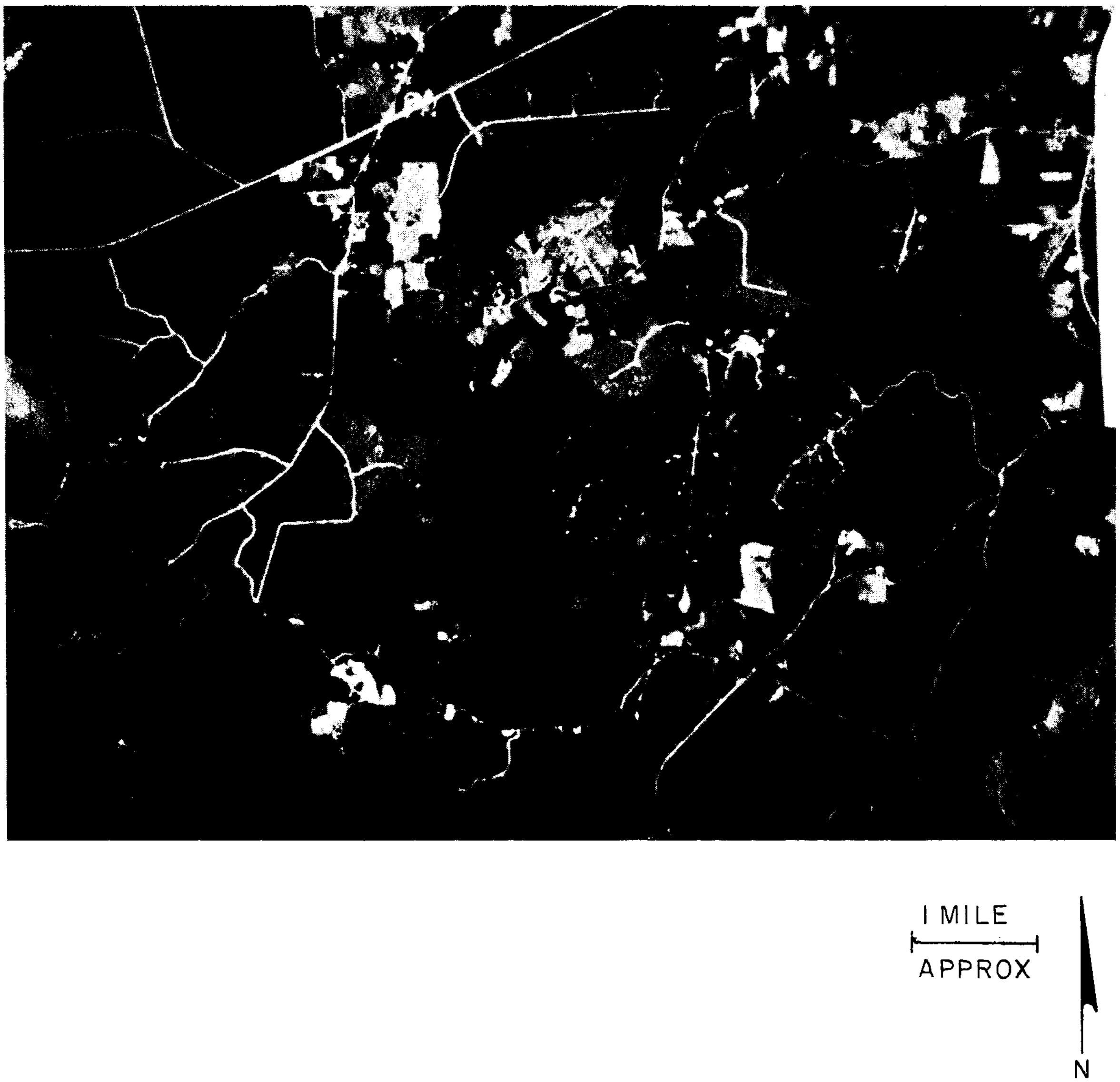


Figure 48. C-IR reproduction of Willis Formation in east Texas. Symbol (a) represents lighter-toned vegetation growing in poorly drained soils (b) dark-toned pine forests on well drained soils.

those growing on sandy soils. The unhealthy trees appear as lighter tones on CIR and black and white aerial photography. In south Texas, the lag deposits often appear as forested patches surrounded by cultivated finer grained soils (Figure 49). Care must be taken in analyzing aerial photographs because subtle tonal variations are often obscured by local land use patterns.

Field Reconnaissance and Evaluation of Deposits

Specific deposits selected from the photographs can then be verified with a field reconnaissance phase. Once a deposit has been located, it can be sampled with a portable auger drill, post hole digger, or even a shovel. A smaller scale sampling program is possible since these deposits are usually at the surface and are fairly thin.

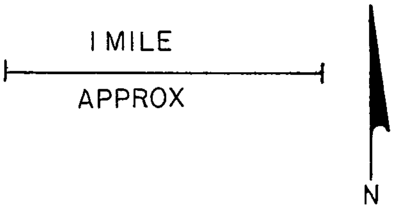


Figure 49. Black and white photograph of Willis Formation in South Texas. Arrow is pointing to forested area on gravel bearing soils. Cultivated land is on finer grained soil.

CONCLUSIONS

The use of an integrated exploration program to find aggregates in the Texas Gulf Coast can save both time and money. The techniques described in this manual will reduce or eliminate the amount of exploration that is done in those formations that do not contain aggregates, and they reduce the amount of drilling involved in locating and defining a deposit.

The exploration approach relies heavily on the use of geology and remote sensing techniques. Historical geology is used to determine which formations contain aggregates. A close analysis of the geological systems existing at the time of deposition helps determine where aggregates will be concentrated. A knowledge of the physical characteristics of the deposits is used with remote sensing techniques to locate specific prospects.

Cemented sandstone deposits are found in the Catahoula Formation. These deposits occur within the crevasse splay subfacies. The sandstones are very erosion resistant and have a well defined joint pattern. In east Texas, pine trees do not thrive where they grow over near-surface sandstones. In south Texas, vegetation grows in linear bands along fractures. Subsurface sandstones form relatively horizontal, dense layers that should have a high acoustical velocity relative to the surrounding unconsolidated materials.

River gravels occur in the ancient terrace and floodplain deposits that border the major rivers in the Texas Gulf Coast. Specific gravel deposits occur in point bars, in simple valley fills, at local tributary influxes, at nickpoints, and on the downthrown side of growth faults. Point bar deposits often have a well defined surface expression. The remaining types are buried by fine grained floodplain deposits.

High gravels are composed of ironstone nodules and siliceous pebbles that are found on hilltops in the Willis Formation. Pine trees growing over high gravels in east Texas are not as healthy as trees growing over sandy and silty soils. In south Texas, gravel deposits are covered by trees and the fine grained soils are occupied by cultivated lands.

If the highway department has a specific type of aggregate in mind, they can go to the formation that contains that aggregate and apply the following techniques:

SANDSTONES

1) Locate outcrop belt of the Catahoula Formation from geologic maps.
2) Locate high potential target areas from sand isolith maps.
3) Locate prospects that show up as regions of high relief on topographic maps or show up in east Texas as unhealthy vegetation and rectangular ground patterns of color infrared aerial photographs in south Texas.
4) Define depth of cover and lateral extent of deposit with seismic refraction techniques.
5) Sample with a drilling rig capable of cutting a solid core.

RIVER GRAVEL

1) Locate ancient and recent terrace and floodplain deposits bordering major rivers cutting across the Gulf Coast (use geologic maps).

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5) Sample with a drilling rig capable of cutting a solid core.

RIVER GRAVEL

1) Locate ancient and recent terrace and floodplain deposits bordering major rivers cutting across the Gulf Coast (use geologic maps).

2) Look for point bar deposits on topographic maps or black and white aerial photographs and/or look for areas where the river channel exhibits high sinuosity and high gradient.

3) Define the lateral distribution of the deposit using electrical resistivity techniques.

HIGH GRAVEL

1) Locate the outcrop belt of the Willis Formation from geologic maps.

2) Look for prospects that show up in east Texas as unhealthy pine trees in Color Infrared or black and white aerial photographs or look for forested regions surrounded by cultivated land in south Texas that show up on any aerial photograph.

3) Evaluate the prospect with a portable auger rig, post hole digger, or even a shovel.

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