SURFICIAL GEOLOGY OF THE HOUSTON AREA: AN OFFLAPPING SERIES OF PLEISTOCENE (& PLIOCENE?) HIGHEST-SEALEVEL FLUVIODELTAIC SEQUENCES

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ABSTRACT

Most near-surface sediments around Houston were deposited by the Brazos and Trinity rivers during Pleistocene interglacial (high sealevel) stages as a series of offlapping, seaward-thickening, fluviodeltaic sequences. During glacial stages, the landward portion of these sequences was exposed to weathering and erosion before the next high-sealevel strata were deposited. Slow southeast regional tilting elevated the exposed sequences enough that some were never covered entirely by later deposits. These updip margins, termed coastal terraces, now form most of the land surface in the Houston area.

Each coastal terrace south of upper Spring Creek has its own pattern of former natural levees, termed *meander-belt ridges* (MBRs), which degrade increasingly landward. The MBR pattern on younger terraces truncates those on contiguous older ones and so initially blocked their seaward-flowing drainage. The drainage ponded and broke through the truncated MBRs, forming larger streams that closely follow the sequence boundaries, herein termed *gathering* streams. Practically all the rest of the present-day drainage follows former back-swamps and flood-basins, leaving the MBRs as divides, even on the youngest terrace. This inversion of the drainage and development of gathering streams makes it possible to reconstruct the MBR patterns from the drainage, even where ridge preservation is poor.

The MBR patterns in a 5,700 mi^2 area were mapped from USGS topographic sheets, to produce an improved areal geologic map based on these *genetic* relationships, *i.e.*, the final sediment transport routes and depositional sequence boundaries. These contrast with traditional mapping criteria which, in the usual absence of outcrops, depend largely on modification by later processes, such as regional tilting and intensity of soil development.

The new map shows that, since deposition of the Pliocene Goliad Formation, eight coastal terraces separated by gathering streams have built eastward from the present Brazos Valley toward the relatively sediment-starved San Jacinto Valley and its Galveston Bay estuary. Farther east, the Trinity River contributed equivalent terraces directly and by occasionally occupying the San Jacinto Valley. It now appears that stratigraphic sequences representing all the Pleistocene highest sealevel stages of Beard, Sangree, and Smith (1982) may be present at the surface in this area, as well as two "extra" ones in the Plio-Pleistocene transition.

INTRODUCTION

The City of Houston occupies the middle third of an approximately 90 mile wide Pleistocene outcrop belt that extends inland from a narrow fringe of Holocene coastal sediments. The near-surface strata within this belt have been deposited by the local rivers as a series of offlapping, seaward-thickening fluviodeltaic sequences, during maximum flooding intervals of the Pleistocene (and perhaps late Pliocene) high sealevel interglacial stages. The exposed landward portions of these fluvial depositional surfaces, termed *coastal terraces* have been modified subsequently by running water and soil development, the effects of which increase inland with the age of the strata.

Meander-belt ridges (MBRs) are the most characteristic and enduring constructional landform on all but the very oldest coastal terraces, having developed by degradation of the natural levees along former *depositing* rivers and streams by redistribution of their materials. Early one-foot contour-interval USGS topographic sheets, available for part of the area, provide excellent information on these features, as Figure 1 demonstrates. Some of the late Pleistocene MBRs that were occupied for an unusually long time are as broad as 5 mi and rise 10 ft above the adjacent minor drainages. At the other extreme, a few MBRs along the middle section of the small, formerly clear San Jacinto River, consist almost entirely of a curving line of low, somewhat arcuate mounds, presumably sandy point-bar remnants.

Each coastal terrace has its own distinctive pattern of MBRs, which truncates that of adjacent older terrace(s), creating "topographic unconformities" that mark the approximate surface trace of the sequence boundaries between them. The truncating MBRs also blocked the drainage of the adjacent older terrace(s), pooling the runoff to where it broke through the truncation to establish a new route to the sea along the landward flank of the truncating MBR(s). This process created the four prominent east-flowing streams in and near Houston—*upper* Spring Creek that forms the northerly line of Harris County, Cypress Creek, Buffalo Bayou through Houston, and Clear Creek along the county's south line, all of which rise on the

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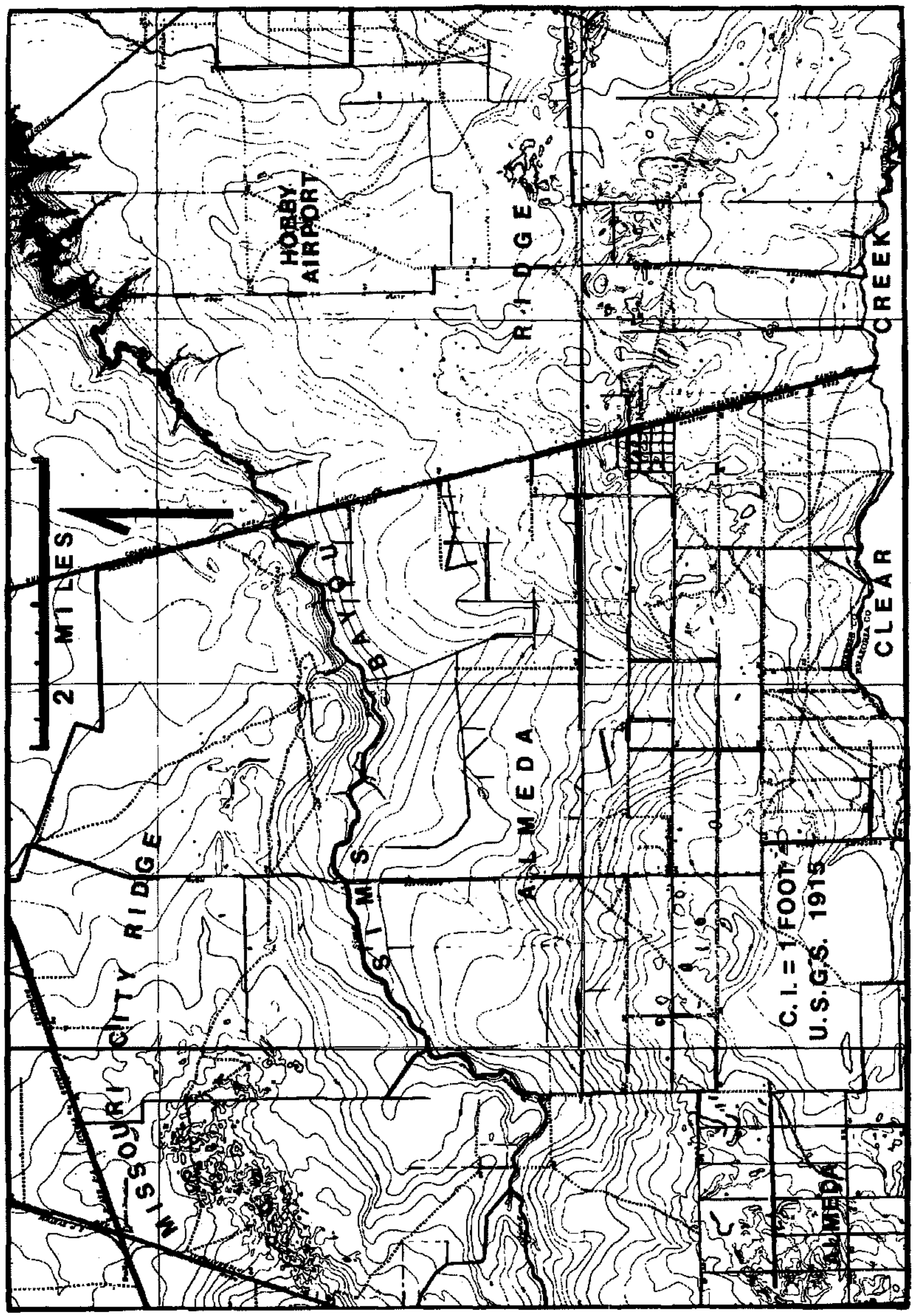


Figure 1. Missouri City meander-belt ridge on northwest, overlapped at Sims Bayou by branch off Almeda ridge in southern outskirts of Houston.

eastern divide of the Brazos Valley and flow into the San Jacinto River or its Galveston Bay estuary. I will refer to these, and to Brays and Sims bayous that also head close to the Brazos and separate smaller coastal terraces between the last two above, and others, as *gathering streams*.

Recognition of the truncations and gathering streams between exposed sequences makes it possible to map the areal geology of this relatively youthful depositional landscape primarily from the *continuous* topographic surface, rather than from isolated, transient, and frequently enigmatic exposures characteristic of the Coastal plain, or from other more indirect criteria. This is greatly facilitated in the Houston area by the availability of one-foot contour interval topographic sheets for all of Harris and Galveston counties, surveyed in 1914 to 1926 by the U.S. Geological Survey. The continuous data supplied by these excellent maps, plus the potential availability of unusually abundant data from excavations, soil boring descriptions, and geophysical logs of boreholes a few hundred feet deep, make the Houston area a particularly favorable place in which to investigate the near-surface Plio-Pleistocene geology of the northwestern Gulf Coastal Plain.

The river responsible for most of this landscape is the Brazos, which heads on the High Plains (Llano Estacado) and brings by far the most detritus to the northwestern Gulf Coast; it and the Colorado River (supplying about 30% as much) together have filled with Holocene sediments a former estuary about as large as present Galveston and Trinity bays combined. In contrast to this, the Trinity River east of Houston, which heads on the lower plains of northern Texas, carries only 20% as much sediment and has barely begun to fill its estuary, Trinity Bay (LeBlanc and Hodgson, 1959). Transfer of this detritus from the eastern slope of the rising western Cordillera to the subsiding northwestern Gulf of Mexico has slowly tilted this entire region toward the Gulf, generally elevating what is now land while the sea floor subsided, so that the coastal terraces have been tilted gently seaward, increasingly with age.

The much smaller rivers that drain the Coastal Plain between these three larger rivers, the San Bernard (west of the Brazos) and San Jacinto (east of Houston), contribute very little sediment themselves, but their lower valleys have been occupied occasionally by one of the adjacent larger rivers, which contributed abundantly. This arrangement has left the area from the San Jacinto River eastward into Louisiana relatively sediment-starved, which led to the Brazos building its coastal terraces primarily toward the east, into what is now the valley of the San Jacinto River or Galveston Bay. This direction appears to have become established by late Pliocene time and persists to this day, so that an almost complete terrestial record of the maximum flooding intervals appears to be present east of the Brazos between Texas City and Willis.

EARLY EVOLUTION OF THE YOUNGEST PLEISTOCENE COASTAL TERRACE

Figure 2 shows the MBRs that formed on the Brazos River portion of the youngest coastal terrace, which formed during the last interglacial stage about 35,000 to 20,000 years ago, and the relationship of its modern drainage to these MBRs. This terrace is bounded on the north by the youngest gathering stream, Clear Creek, and on its other sides by Holocene sediments of the Brazos flood plain and those along Galveston Bay and the Gulf of Mexico. The truncated tips of the MBRs on the next-oldest coastal terrace, visible along the north edge of Figure 2, demonstrate that Clear Creek is indeed a gathering stream. Some of the MBRs south of Clear Creek are represented on this figure by their meandering final channels, which are visible almost continuously on early aerial photographs, but others had to be represented by heavy black lines, which usually show only the generalized "topographic axis" of the meander belt. Each of these meander belts (except a partly buried one) heads at the eastern edge of the Brazos floodplain; some branch *down*stream, and all the principal ones continue "ungathered" east-to-south into Galveston Bay or other coastal waters. One of these latest Pleistocene channels has even drawn water from the Brazos in the Holocene; this is Mustang Bayou (Blue Ridge) above Alvin, which had *re*established headwaters on the Brazos flood plain at Sugarland in the present high sealevel stage! Nevertheless, all the MBRs have become present drainage divides, so that the modern drainage follows the former backswamps and flood basins. This inversion of the stream pattern means that even on the earliest Pleistocene coastal terraces, where the MBRs have been obscured or perhaps destroyed, their general pattern, and the boundaries of the coastal terraces, can be reconstructed from today's drainage network of consequent and gathering streams!

STRATIGRAPHY

Figure 3 presents the basic stratigraphy and legend for two complementary regional maps, which also show most of the natural drainages. Figure 3A lists the stratigraphic names used herein for the *coastal* terraces and for the equivalent *river* terraces, with the columns *inverted* to match their relative position on the regional maps, along with the patterns (or absence thereof) that represent them and the symbols utilized.

Figure 3B shows on the left the stratigraphic divisions and names that seem most appropriate for the Houston area, along with what I believe to be the most nearly equivalent ones used by the more active investigators during the last 50 years. The older names that I continue to use are those proposed by Doering, shown in the right column, which are based primarily on the dependent variables of ground elevation, slope and proximity to the Gulf, which yield results that are broadly comparable to my MBR patterns but much less detailed. The second column from the right lists the terms proposed by Fisk

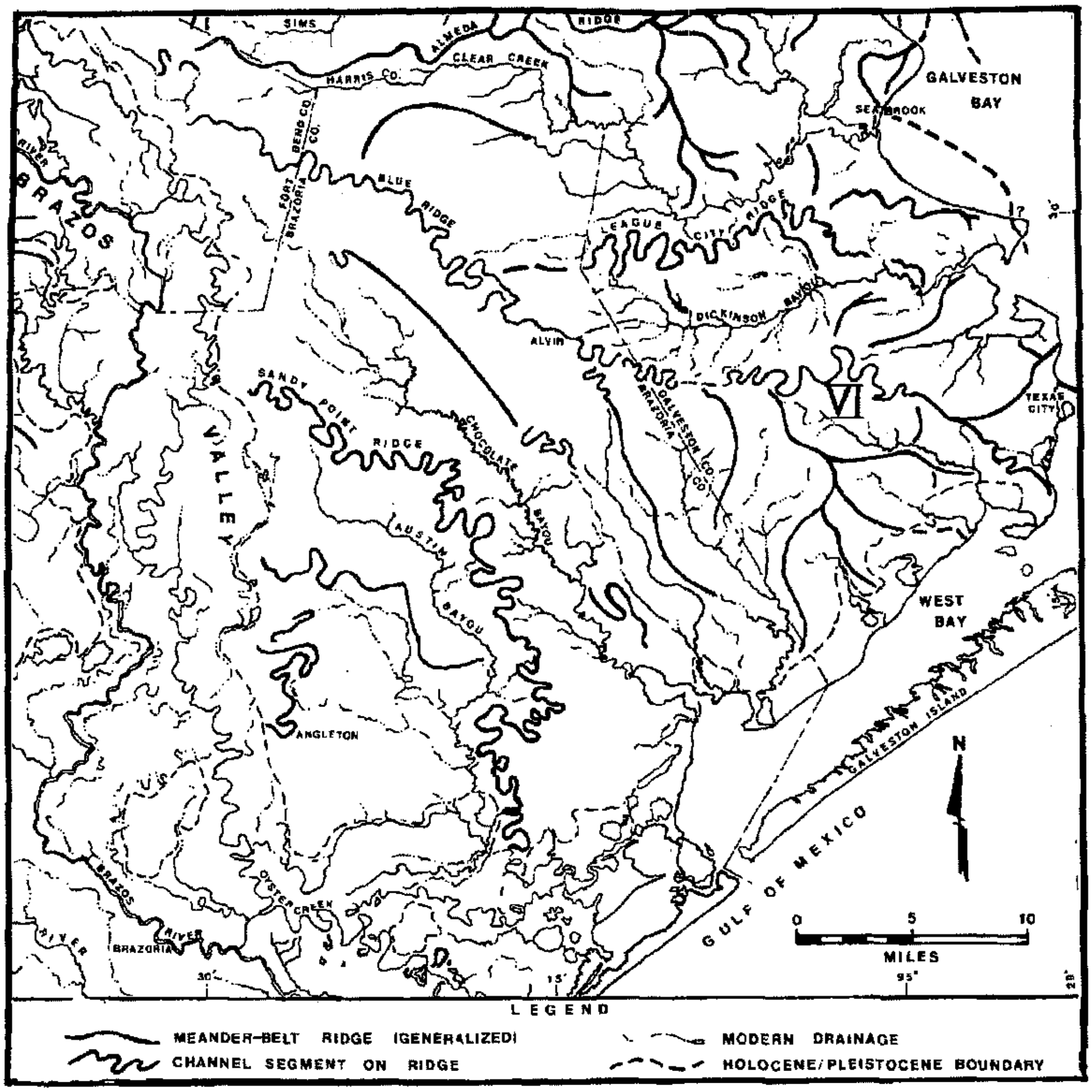


Figure 2. Late Pleistocene meander–belts and modern drainage south of Clear Creek, the gathering stream that marks the northern edge of the Eunice coastal terrace. The present streams within this youngest coastal terrace follow the low ground between ridges (with one exception) and flow separately into the bays.

for fluvial terraces in Louisiana; however, these really are not appropriate for the distinctly different coastal terraces and appear to have been used inconsistently by previous authors. I now employ three informal names, indicated on this figure (only) by parentheses. These are *Almeda* for the distinctive coastal terrace formed from detritus brought in along Barton's (1930) Almeda (meander-belt) ridge; *Tomball* because the name Bentley is inappropriate and the distinctive characteristics of that unit are best seen around the town of Tomball; and *Freeport* for the incipient Holocene coastal terrace begun as the joint deltaic plain of the Brazos and Colorado rivers inland from that city. Also, like Bernard and LeBlanc (1965) I extend the Goliad Formation into the Houston area, much farther east than shown on previously published mapping.

For the fluvial terraces I use the Austin-area names proposed for the Colorado River by Weeks (1941), since they fit the Brazos almost exactly, having been controlled by the same cyclic changes in sealevel. The flood plains of the two rivers obviously correlate, the Gay Hill terrace is practically continuous from one river valley to the other along the crest of Gay Hill (the Oakville Fm. cuesta), and the spacing and character of the intervening terraces are similar.

THE REGIONAL MAPS, FIGURES 4 & 5

Figures 4 and 5 cover a 53 by 84 mile area inland from most of Figure 2; it includes all of Harris and Waller counties, about half of Austin and Fort Bend, and minor parts of 9 additional

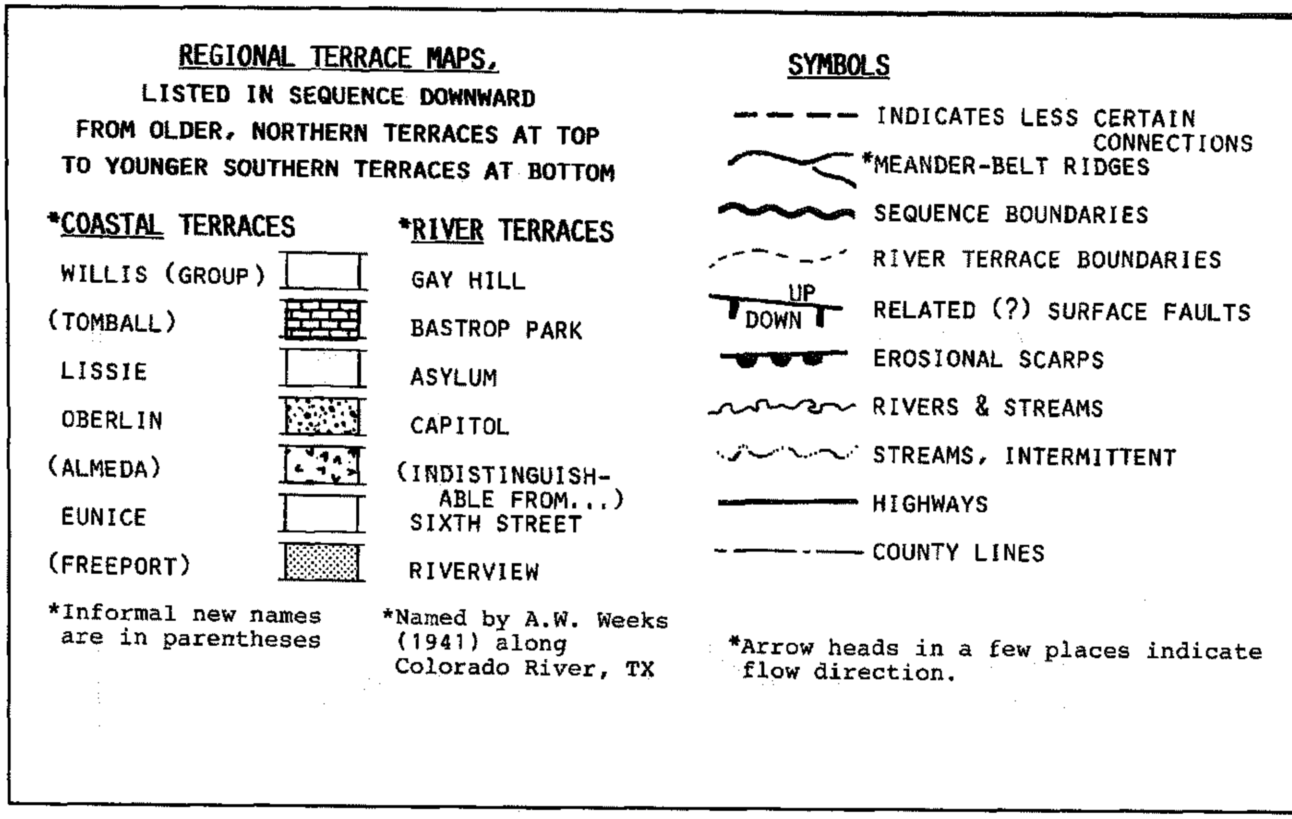


Figure 3. 3A Legend for regional terrace maps, Figures 4 and 5.

GEOL. AGE		TEX. FLUV. TERR.	THIS PAPER		VAN SICLEN 1985	BARNES, ET AL. 1982	BARNES, ET AL. 1968	BERNARD & LE BLANC 1965	FISK 1938 & 1940	DOERING 1935 & 1956
PLEISTOCENE	UPPER	SIXTH STREET	BEAUMONT GP.	EUNICE	EUNICE	BEAUMONT	BEAUMONT	PRAIRIE OR BEAUMONT	PRAIRIE*	EUNICE*
				(ALMEDA)	ALMEDA					
		CAPI-TOL		OBERLIN	OBERLIN				MONTGOMERY*	OBERLIN*
	MIDDLE	ASYLUM	LISSIE		LISSIE	LISSIE	MONTGOMERY	MONTGOMERY OR UPPER LISSIE	BENTLEY*	LISSIE
	LOWER	BAST'P PARK	(TOMBALL)		BENTLEY	WILLIS	BENTLEY	BENTLEY OR LOWER LISSIE	WILLIANA*	WILLIS*
		GAY HILL	TWO UNNAMED UNITS		WILLIS REGOLITH		WILLIS	WILLIANA OR WILLIS		
PLIOCENE			"TYPE" WILLIS							
			GOLIAD		GOLIAD	TERTIARY	FLEMING	GOLIAD	TERTIARY	

3B Evolution of local Pleistocene stratigraphic recognition, correlation, and nomenclature.

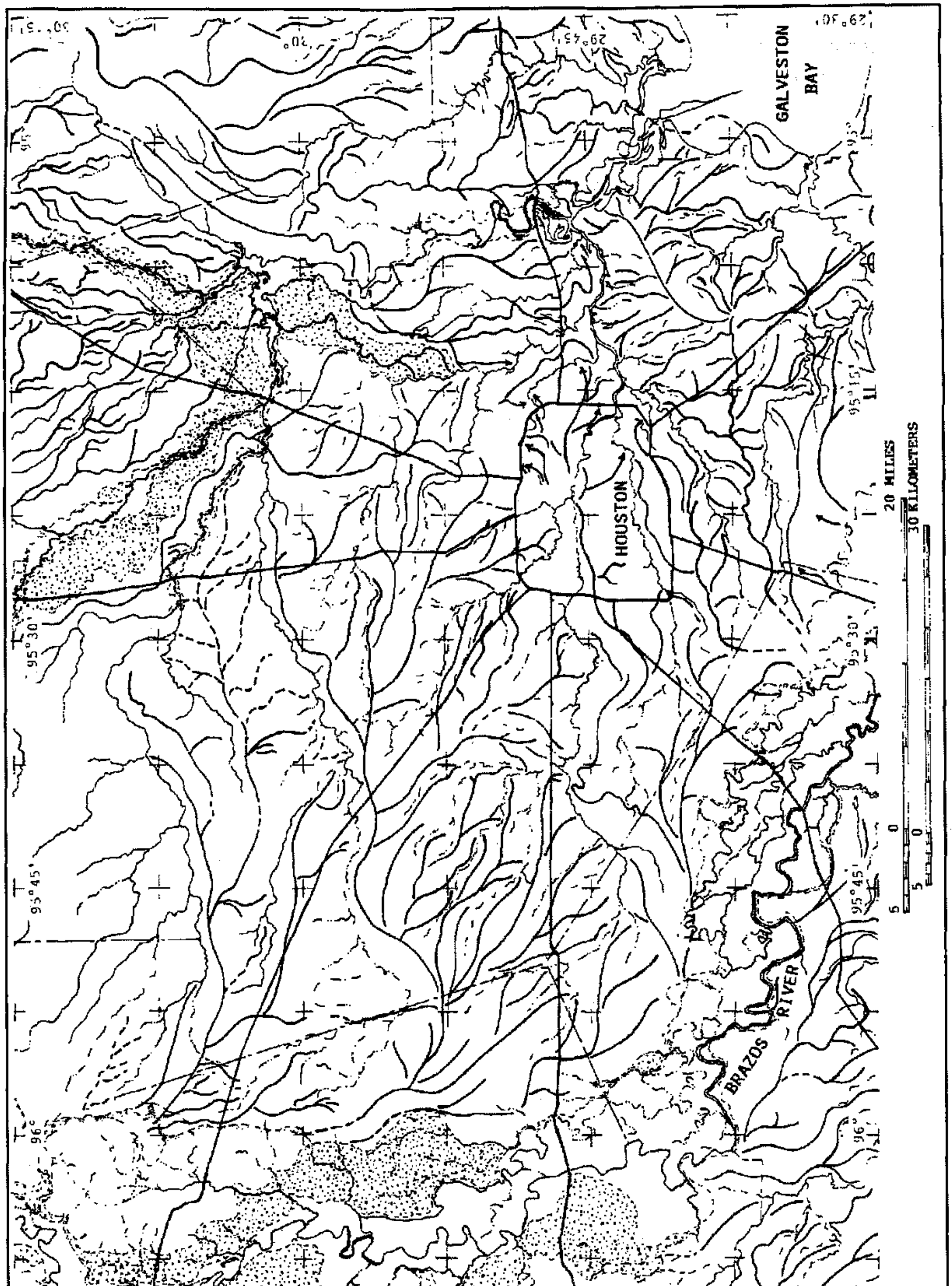


Figure 4. Meander-belt ridges on the coastal terraces between Colorado River deltaic plain in extreme southwest corner and Trinity River floodplain at northern east edge. Also, fluvial terraces along the Brazos and San Jacinto valleys are outlined by short-dashed lines and alternate ones are marked with the same patterns as equivalent coastal terraces. For little-eroded younger terraces along these valleys this is a valid areal geologic map. See Figure 3A for map symbols, patterns and stratigraphy.

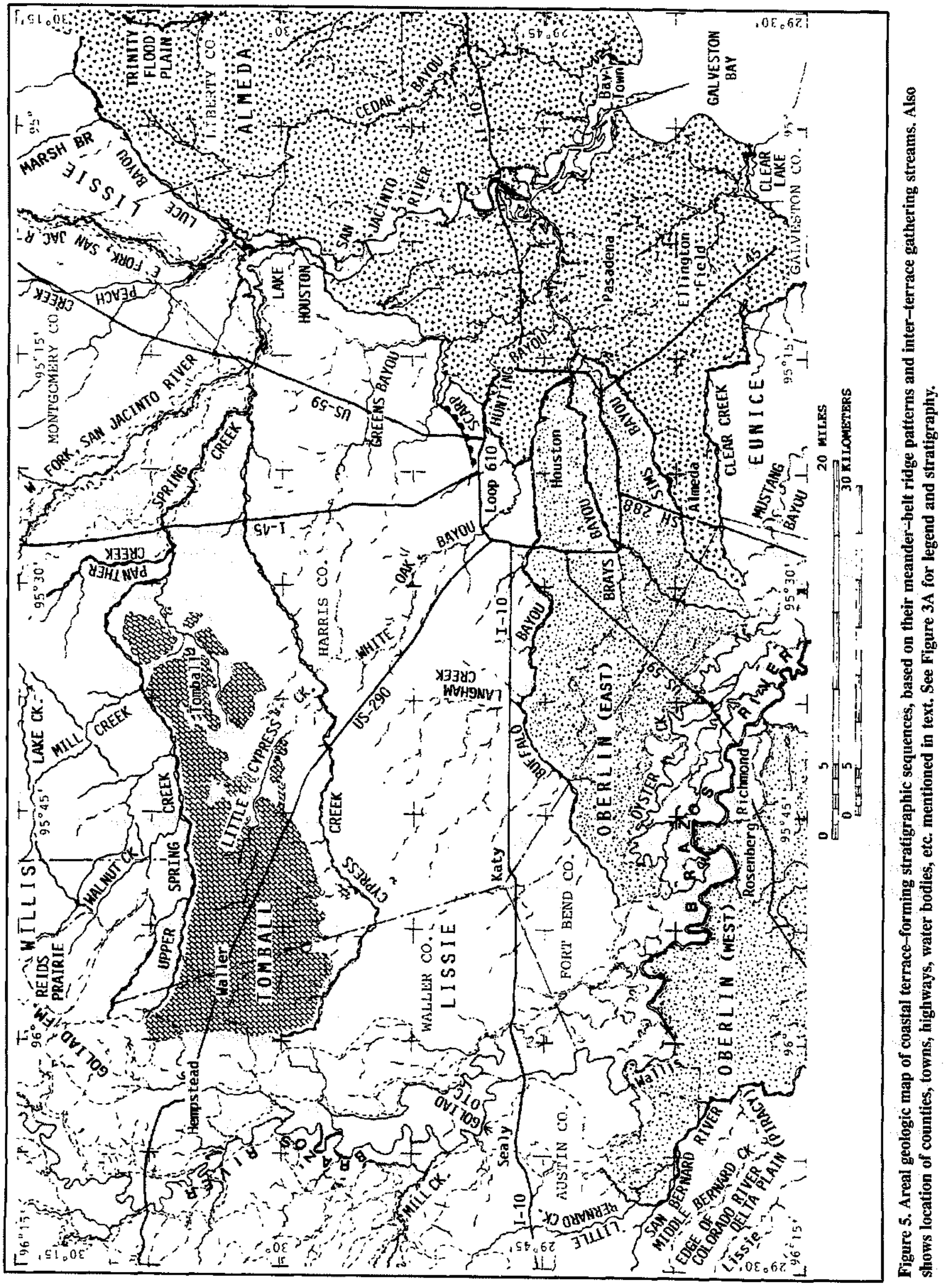


Figure 5. Areal geologic map of coastal terrace-forming stratigraphic sequences, based on their meander-belt ridge patterns and inter-terrace gathering streams. Also shows location of counties, towns, highways, water bodies, etc. mentioned in text. See Figure 3A for legend and stratigraphy.

counties. These maps are based on a solid block of 66 U.S. Geological Survey 7.5 minute topographic quadrangle sheets: the most detailed data came from the 1915–1926 *one* foot contour interval sheets for Harris and Galveston counties and the rest from later sheets with five and (in the extreme northwest) ten foot contour intervals. Physiographically, this region extends from the very edge of the Holocene flood plain of the Trinity River in the northeast, nearly to that of the Colorado River in the southwest corner. Stratigraphically, it extends from the northern edge of the youngest Pleistocene coastal terrace shown on Figure 2, across the older Pleistocene coastal terraces onto probably uppermost Pliocene clay-rich strata above the more gravelly Goliad Formation. The latter rests on the clay-rich late Miocene Lagarto (or upper Fleming) Formation in the northwestern corner of the maps, although those pre-Pleistocene unit boundaries are not indicated on it. This then is a very representative sample of the surprisingly varied surficial geology of the greater Houston area! The scale reduction needed to fit this volume, however, makes it necessary to place virtually all the identifications on Figure 5, only, so it must be referred to when using Figure 4.

The MBRs on Figure 4 are mapped because almost all represent the approximate average position of the final depositing streams that initially shaped most of this land. As such, they reveal the general direction from which these sediments came; and their coherent patterns, particularly the truncations and gathering streams, enable the depositional sequence of the terraces to be determined conclusively and their boundaries mapped more accurately than from previously-used criteria. Thus MBR mapping is based on *genetic* relationships of the near-surface sediments whereas the traditional criteria depend mostly on the operation of *later* processes, particularly regional tilting, intensity of soil development, and degree of local erosion and redistribution of their materials. Furthermore, the topographic data are relatively objective, potentially continuous, and readily available. The present investigation is the first extensive use of MBRs for areal geologic mapping of exposed offlapping depositional sequences that I am aware of, although it would appear to have wide applicability to coastal plains elsewhere.

Although Figure 4 is primarily a compilation of the more evident MBRs on the coastal terraces, it also shows the approximate areal extent of the equivalent fluvial terraces along the Brazos and upper San Jacinto valleys when the river last flowed against them. To the degree they are preserved, they demonstrate that as the MBRs converge upstream, the trunk ridges originally continued onto equivalent fluvial terraces. For convenience, these are represented here by the same map patterns as the correlative coastal terrace(s) on Figure 5. However, most of the material of the *older* fluvial terraces, beginning locally with much of the northern Asylum (= Lissie) terrace, has been largely eroded away so that only the underlying regional stratigraphic units generally remain. Consequently, as an areal geologic map, this is valid for only the intact, generally younger fluvial terraces.

Figure 5 is a geologic map of the near-surface strata beneath the coastal terraces only, based primarily on the MBR patterns of Figure 4, and their compatibility with the persistent fluvial terraces, which are merely outlined on this map. On both maps the dotted pattern along the Brazos and San Jacinto rivers represents their flood plains, properly the *Riverview* terrace, which divide the area into three convenient sub-regions. We'll consider these in turn, beginning west of the Brazos and circling counter clockwise to the northeast corner of the map, before moving into its central part. This will be followed by the related forks of the San Jacinto sector and finally the Plio-Pleistocene transition area to the west, in the central-northern part of the maps.

DESCRIPTION OF THE COASTAL TERRACES, FIGURES 4 AND 5

The Area West of the Brazos River

Due west of Houston, the town of Sealy (Figure 5) straddles the irregular overlap of an abbreviated Pleistocene section onto the Pliocene Goliad Formation, which creates the first rocky outcrop up the Brazos. This is located 0.2 mi northwest of the statue of Stephen F. Austin, in S.F.A. State Park four miles northeast of Sealy. Here the Goliad consists of sandstone, some quite pebbly, overlain by hard white clay, and has an exposed thickness of about 40 ft. In the hilly terrain back toward Sealy, several excavations and road cuts have exposed leached and oxidized sand and clay that is probably basal Willis Formation in its normal stratigraphic position. In this case, it appears to have been truncated by the Brazos to prepare the base for a thin covering of Asylum (=Lissie coastal terrace) sediments, so the distinctive regolith on top of the "type" Willis is missing. This and other considerations suggest that Willis beds may also be present at shallow depths (and possibly crop out locally) in the extensive area southwest of Sealy that is shown as Lissie on the Geologic Atlas of Texas map.

Along Texas Hwy. 36 at and beyond the north edge of Sealy, the Goliad crops out intermittently for several miles on the scarp between the Asylum and Capital terraces, and more extensively somewhat west of this highway. North of the broad valley of Mill Creek, weathered Goliad is exposed in numerous shallow cuts along FM 529 between Burleigh and Bellville, where powdery white caliche is surprisingly common but difficult to recognize except after a good rain. From Mill Creek to the northwest corner of the maps, very little true Asylum sediment (except residual gravel) is likely to be found within the range of elevations valid for this terrace. The same is even more likely for Bastrop Park terrace material along the entire west edge of the regional maps.

South of Mill Creek, however, the Asylum terrace appears to have been maintained by occasional deposition, still graded to the original Asylum "level", of alluvium off the gentle southeastern dip slope of the southward-plunging Goliad cuesta that tops out along the east side of the Colorado River Valley; this process may have continued intermittently ever since deposition of the Asylum "age" sediments. The wet-weather depositing streams that formed these small natural-levee ridges (not strictly MBRs) are distinguished on the map by the addition of arrow heads, which also confirm their flow direction. Although graded to the Asylum terrace of the Brazos, these low ridges are, in a sense, part of East Bernard Creek's section of the miniscule deltaic plain of the San Bernard River, which grades into the northeast edge of the Colorado River section of Lissie coastal terrace. Except in its headwaters, the San Bernard River in this area follows the overlap of the Oberlin coastal terrace to the east onto that river's tiny strip of Lissie deltaic plain along its west side, as shown on Figure 5.

Coastal Terrace of the Almeda Member of the Eunice Formation

Crossing the Brazos to the lower central part of the regional maps, we will consider a very distinctive element of the Almeda coastal terrace, located immediately north of Clear Creek, south of Sims and Buffalo bayous and west of the San Jacinto River and Galveston Bay. That fan-shaped area was served by a long-lived meander belt of the Brazos, which then continued east from near Richmond instead of turning back to the south as it does today. From a slim base along the Riverview terrace, this Almeda MBR pattern expands eastward into a fairly symmetrical bird's-foot delta centered just north of Ellington Field, which is referred to as the *Pasadena delta*. It is unique for the inland Houston area in showing evidence of at least three straight deltaic distributing channels slightly south of the San Jacinto Monument and several low recessional shoreline scarps on its southeast flank in the Bayport industrial area.

This low-energy delta was protected by the Ingleside barrier island system (Price, 1933), the nearest exposed remnant of which is at Smith Point, the prominent peninsula east of Galveston Bay, between Trinity and East bays, where the Ingleside barrier has turned inland towards its eastmost occurrence near Lake Charles, LA. The Eunice terrace, which formed during the high sealevel event that followed construction of the Pasadena delta, breeched and covered most of this eastern Ingleside segment, which confirms its presence during the preceding Almeda high-sealevel event.

An adjacent, larger area of Almeda terrace is located north of Buffalo Bayou, along the lower San Jacinto Valley and east to that edge of the maps. It overlaps the Lissie Formation to the west from inside the northeastern sector of Houston's Loop 610 to almost half-way up these maps, where a strip of Capitol terrace comes between them northward to Luce Bayou, a gathering stream that marks the Almeda/Lissie boundary farther northeast. The MBR pattern southeast of Luce Bayou demonstrates that the nearby Trinity River to the east is the source for these ridges. Cedar Bayou in the central part of this Almeda area is an *internal* gathering stream between two successive delta lobes, of which the older one on the west was fed by a long-lived meander-belt of the Trinity, successive positions of the lower part of which ultimately covered with sediments a triangular area located on both sides of the San Jacinto Valley that is larger than the Brazos' Pasadena delta. This western lobe is remarkable also in that one of its eastern MBRs originally continued across the head of Galveston Bay to near Seabrook, where it seems to have interacted with the contemporary eastern edge of the Pasadena delta.

The small piece of Almeda terrace occupying most of the northeast quadrant inside Loop 610 east of *lowest* White Oak Bayou and extending east of the Loop to lower Hunting Bayou, received its sediment from strictly local sources. Most was brought in by Buffalo Bayou, as indicated by the short MBRs tipped by arrowheads on Figure 4; some may have arrived in floodwaters escaping from the Brazos, and White Oak Bayou must have contributed as well. An extraordinary source was erosion, probably in part by waves, of a headland that projected into the Almeda estuary, formed by the confluence of two large Lissie MBRs slightly northeast of the intersection of North Loop 610 and I-45. Erosion of this headland left a unique, northeast-trending sea cliff, now flattened into a long gentle scarp that rises above uppermost Hunting Bayou to about 65 feet above present sealevel, as indicated by a line of semicircles on Figure 5.

The Oberlin Coastal Terrace

This is the only coastal terrace that is well developed on both sides of the Brazos River. The larger, western portion represents a successful attempt by the Brazos to reverse earlier encroachment by the Colorado delta by maintaining its own course due south past Wallis, rather than making the big eastward swing of the present river past Rosenburg and Richmond. As noted above, this Oberlin overlap onto the Colorado River's Lissie terrace forced the intervening San Bernard River into its present course along this formation contact. A very few bits of original MBR channel are visible on early airphotos of the western Oberlin area, but I have not seen any in the eastern area, which suggests that the western Oberlin is slightly younger than that across the river.

East of the Brazos, the Oberlin terrace occupies the area between Buffalo Bayou and Sims Bayou, west to the Riverview terrace; this includes most of the area inside Loop 610. Willow Waterhole Bayou and lower Brays Bayou separate it into two lobes, the older northwestern lobe occupying almost three times the area of the southeastern one. The eastern Oberlin MBRs appear to have been lowered by accumulation of clay in the intervening areas, possibly brought by flood-waters from the Brazos discharging down Buffalo Bayou. This is feasible topographically, and its' occasional reality is supported by an approximately four inch bed of good reddish clay within the cleaned-up white sand characteristic of the bayous that was formerly exposed in the upper part of the Almeda-equivalent(?) terrace off the southwest corner of the picnic area in Memorial Park, Houston.

Figure 6 illustrates the overlap of Oberlin onto Lissie Formation along Buffalo Bayou. The Clodine MBR enters along the southern west edge of the figure and turns sharply east-southeast to continue along the south side of the bayou. In so doing the river has removed an earlier continuation of the Long Point fault scarp, completely concealing the fault's now-known southwest continuation. Piney Point, a representative example of a large Lissie MBR, is truncated also at the Oberlin overlap. The abrupt change in direction of the north-northeast-flowing reach of the bayou, where it crosses this ridge at a high angle, probably formed when the new Clodine MBR ponded the Lissie drainage, which then overtopped and broke through the Piney Point MBR, thereby contributing to the development of Buffalo Bayou into the gathering stream it now is.

The Lissie Coastal Terrace

The Lissie coastal terrace is the most extensive one shown on Figures 4 and 5, where it occurs in three general areas—a tiny one in the southwest corner of these maps, sourced from the Colorado River; a large area across the middle of them, between Buffalo Bayou and its encroachment onto the Tomball terrace north of Cypress Creek (Fig. 5), sourced by the Brazos and Trinity rivers; and a triangular area west of their northeast corner that was sourced by the Trinity, perhaps with assistance from local sources.

The variety of conditions in the central Lissie area and availability of early one-foot contour interval maps makes this the "type area" for MBRs. Note that the major trunk MBR (then the Brazos meander-belt) comes off the equivalent Asylum fluvial terrace southwest of the Tomball coastal terrace and follows the south side of Cypress Creek, where it fed numerous southeastward-prograding distributary channels. It has quite a few internal gathering streams, like Langham Creek and upper White Oak Bayou, which may have formed when growth of the delta resumed after repeated brief lowerings of sealevel had exposed the delta to limited erosion.

As the Lissie delta advanced eastward into deeper water, it became more symmetrical and widened at the expense of the adjacent Tomball terrace, which had experienced considerable erosion during the preceding low-sealevel stage. The southeastern part of the Tomball, where its MBRs on Figure 4 are dashed, was inundated and received a thin cover of sediments from the Lissie and local sources, which filled the larger valleys and built-up the lower areas to the level of the Lissie terrace. Figure 7 shows the effects of this on the Tomball terrace, and Figure 5 indicates the extent of Lissie encroachment onto it. Nevertheless, I place the boundary between these terraces at Cypress Creek because this is as far as the Lissie MBRs built out into this seamingly very shallow, isolated bay.

The "western" MBR pattern in the central Lissie area is cut off abruptly on the east by a massive Lissie MBR that enters the regional maps on their north edge, and makes the western edge of the valley of the West Fork of the San Jacinto River. It branches as it crosses Spring Creek, but the main MBR continues due south along the west side of the main San Jacinto Valley, with further branching, to where its south tip joins a "western pattern" MBR to form the headland just northeast of the present North Loop 610 – I-45 intersection that later became part of the 65-foot scarp indicated on Figure 5, as noted previously. This MBR rates with the biggest of those from the Brazos, so it must have come from an avulsion of the Trinity River into the San Jacinto's West Fork north of Huntsville.

The smaller, more closely-spaced Lissie meander-belts between the east and west forks of the San Jacinto River may have been fed from local sources to the north. One meander-belt from between these forks does continue part-way down the San Jacinto Valley onto the younger Capitol terrace remnant, which demonstrates the feasibility of this source. Since the length of time represented by the Lissie terrace is much longer than that available for the Capitol terrace (Fig. 8), the northern local sources may have been capable of forming this MBR pattern between the San Jacinto forks, or at least that part of it west of Peach Creek, an internal gathering stream; or all of it may have come with the Trinity River at about the time it formed the big MBR along the west side of the West Fork and of the San Jacinto River itself, as described in the preceding paragraph.

The separate pattern east of Peach Creek could well have formed at the same time as the Lissie MBRs just east of the east fork, by the Trinity River leaving its present course south of Livingston and flowing southwest along low ground into the east Fork near Cleveland. The more widely-spaced MBRs in the far *internal* northeast corner of the regional maps (east of Marsh Branch, a minor internal gathering stream) could have come directly from the Trinity River farther down its present valley.

The Tomball Coastal Terrace

The quality of the MBRs deteriorates in the eastern part of the Tomball terrace due to its considerable deformation and erosion. It is fully adequate, however, in the little-eroded western part, where the mapping is well constrained by the drainage as well as by the topography. The peculiar convolute MBR in the western area that continues south across the headwaters of Cypress Creek is obviously a product of later intermittent local erosion and deposition, so it is not genetically related to the primary MBR about in line with it farther north, although the latter may have served as a source of its sediments. The "MBRs" mapped in the southeastern part of the Tomball terrace appear generally to be compaction highs over shallowly buried MBRs.

Out of probably four coastal terraces between the well preserved Lissie terrace and the Goliad alluvial fan, this is the only

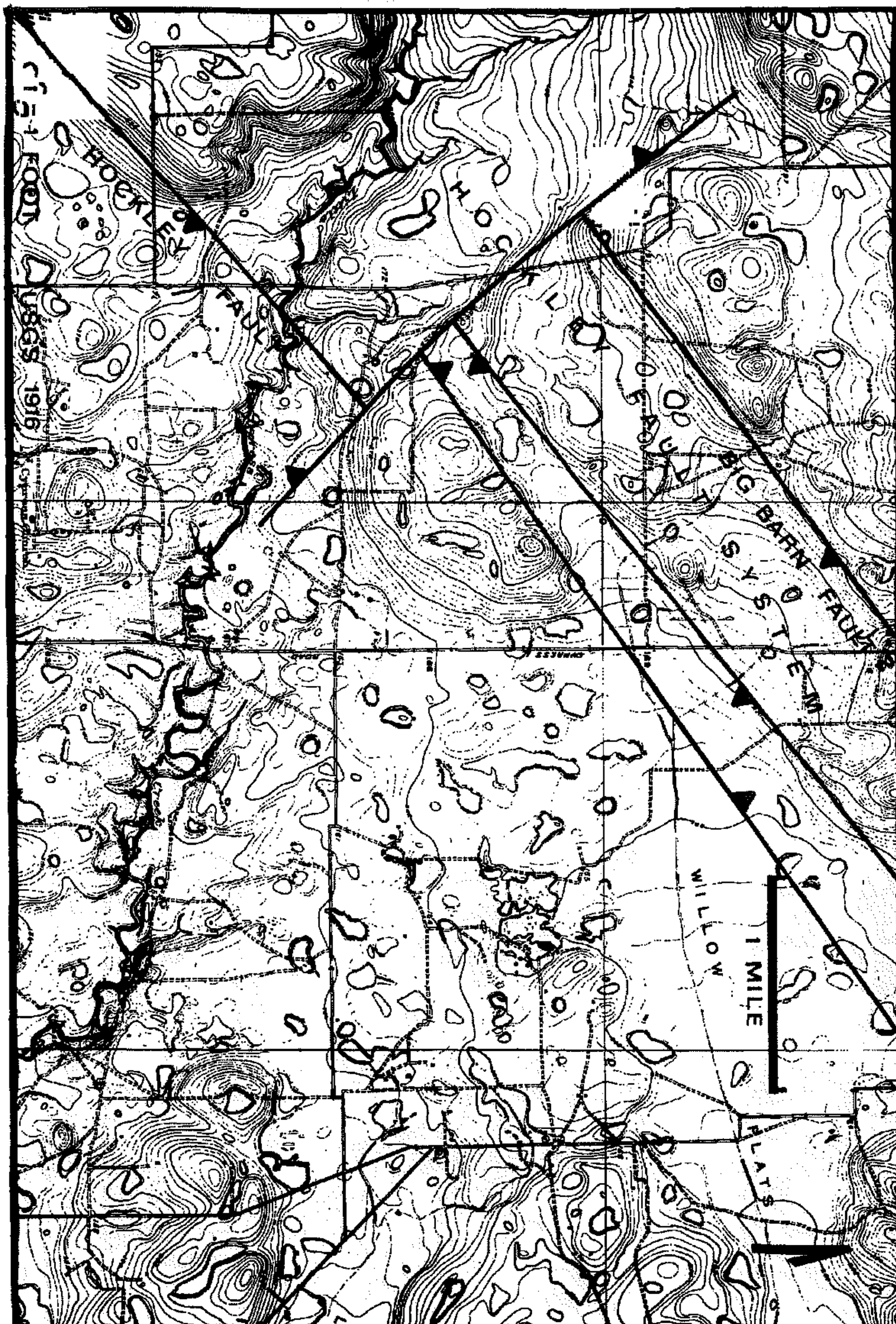
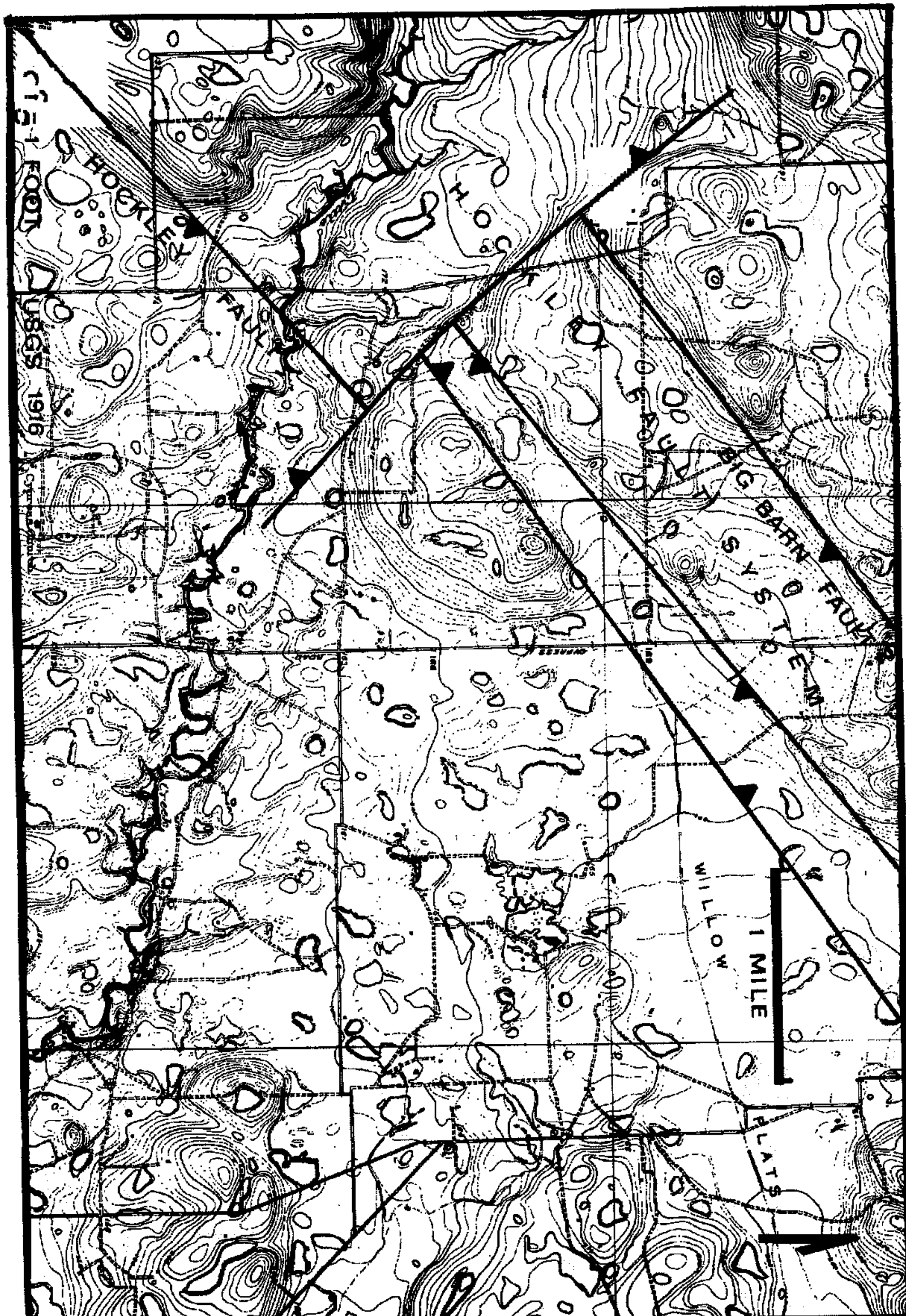


Figure 7. Seemingly steep-sided hills on this 1916 one-foot contour interval topographic map are outliers of the Tomball unit that stick up through onlapping Lissie Formation beneath Willow Flats and other lowlands. Center of this highly faulted area is six miles southwest of Tomball, on southwest flank of Tomball dome two miles southwest of its oil field.



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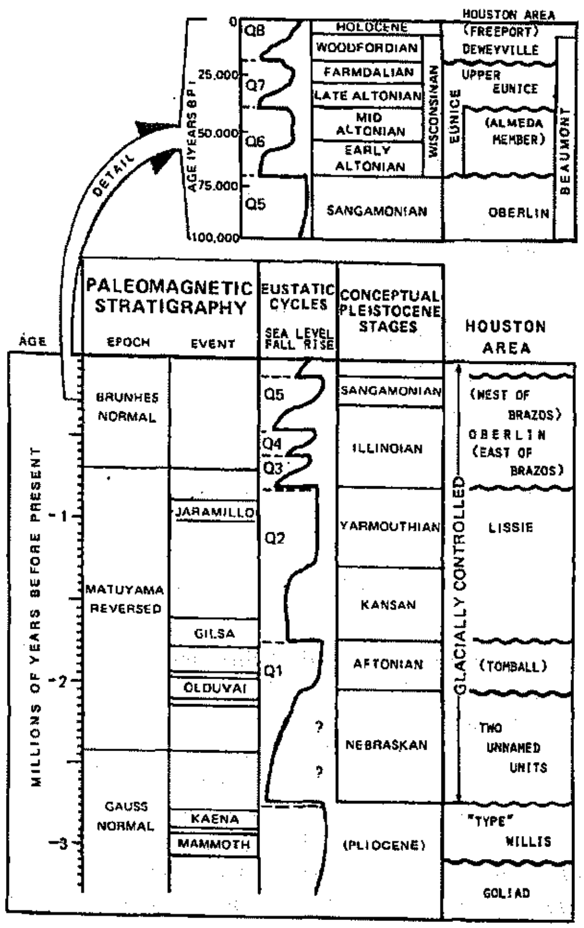

Figure 8. Suggested correlation of Houston–area stratigraphic units with sealevel cycles (after Beard *et al.*, 1982).

one with a mappable MBR pattern. The eustatic cycle chart of Beard *et al.*, (1982) on Figure 8 implies that the Tomball terrace is slightly more than twice as old as the Lissie. This big difference is expressed on Figure 7 as effects of regional uplift, tilting, faulting, and erosion; but to compare the Tomball with the still older terraces, in the absence of reliable MBR patterns, the most diagnostic criteria are likely to be the degree' and character of lithologic changes caused by the weathering processes. In this, the difference between it and the Lissie is striking—the latter has probably been leached locally under some of the closed depressions but is usually calcareous and not noticibly oxidized. I have seen isolated iron oxide nodules that formed in subsoil as young as Almeda, however, and seen those from the Lissie concentrated, along with caliche, as gravel in the lower part of a buried stream channel formerly exposed beneath the terrace fill of White Oak Bayou, but have not seen anything in the younger units that resembles the weathering in the Tomball.

The best place to observe the Tomball weathering that I know of is the drainage ditch along the south edge of the Westbourne Subdivision, located on a low hill a little west of FM 149 about 4.5 mi south of its intersection with FM 2920 in Tomball. The material there has lost all its carbonate and assumed a strong brown iron-oxide color to the very bottom of the 12 foot ditch; it contains clustered grains of sand but no iron oxide *nodules* or siliceous pebbles. Exactly the same sort of material was exposed in the early 1960's in a slightly shallower but poorly-maintained drainage ditch in what is now the eastern part of the town of Tomball. Also I do not recall ever having seen on the Tomball terrace, including the parts farther west and south, the distinctive Willis type of regolith, consideration of which is regretably beyond the scope of this paper.

Coastal Terraces Between Upper Spring Creek and the Goliad Outcrop

The generally rising terrain from upper Spring Creek northward across the irregular Goliad cuesta appears to have preserved a record of the Plio-Pleistocene transition, apparently characterized by domination of the local creeks. North of Figures 4 and 5, the upper reaches of southeast-flowing Mill Creek and especially Lake Creek, which cross the Goliad outcrop in broad open valleys, must have become established on the Pliocene alluvial plain that, for a time, had extended without interruption from the front ranges of the Rocky Mountains to the northwestern shore of the Gulf of Mexico. Barely inside its north edge, Figure 5 does show the segment of each of these creeks that deflects abruptly to the east for distances of 5 and 11 miles, along which both collect runoff from the north, just like the gathering streams that separate the coastal terraces farther south. I have connected these deflections with a sine-curve unconformity line, which continues southwest across a similar but more subdued bend in Brushy Creek (not shown) and a very subdued one on Walnut Creek, and ends at the southeastern edge of Reids Prairie, a unique open, gently sloping plain. This line has the shape of the gathering-stream one would expect to see on a coastal terrace formed by two or more separate creeks or small rivers, as is the case here. The northern boundary of this hypothetical oldest coastal terrace would then be located along the downdip edge of the Goliad outcrop, from the west-to-northwest side of Reids Prairie irregularly east-northeast to and beyond the town of Willis (close to I-45 12 mi north of these regional maps), where the Willis Formation pinches out against the Goliad.

About two-thirds of the distance from the above wavy line to upper Spring Creek, I have added another such line that connects a series of shorter but still distinctively sharp eastward deflections of smaller but more numerous creeks. The topographic sheets show a continuous divide along (and connecting) the south side of the longer eastward-flowing sections of Mill and Lake creeks, which blocks the drainage from the north. Numerous small, ungathered consequent streams like those on the youngest (Eunice, Fig. 2) coastal terrace head along the south flank of this divide, as if it were the remaining "root" of an MBR. Although our observations farther south might lead us to expect these streams to have fed into a single gathering stream like upper Spring Creek, this would not necessarily have occurred in the absence of an eastward component of current regional tilting. In this event, and assuming that the net longshore drift was eastward, it would be reasonable to expect similar deflections of all the creeks along a gently curving, low-energy shoreline like that represented by the second wavey line. The similarity in shape of this hypothetical shoreline to that of upper Spring Creek is encouraging, as is its considerable divergence in an eastward direction to one about parallel to the axis of regional tilting.

The two "possible" MBRs separated by uppermost Spring Creek that are shown on Figure 4 are speculative, but they are indeed ridges that do resemble MBRs. The one southwest of that creek is near and almost parallel to the trunk Tomball MBR and topographically quite similar in every respect, so it might well be an overlapped pre-, or earlier Tomball MBR. The other, northeast of Spring Creek and bounded on the northeast by Reids Prairie, is also a gently-sloping ridge but appears to have been considerably modified by erosion along a number of small intermittent streams on both sides. Its orientation precludes it from being a strike ridge of resistant Goliad material but would be compatible with a fairly straight, gravel-rich channel fill. Both of these features are so located that they might have received the ancestral Brazos River, and their position on a drainage divide may have provided some protection from erosion, so an MBR origin seems plausible, especially for the more southerly one. All these interpretations, however, remain merely strong leads that have yet to be tested on the ground.

Correlation of Coastal Terraces with Glacially-Controlled Sealevel Cycles

Figure 8 correlates the stratigraphic sequences beneath the coastal terraces with the Pleistocene eustatic cycles of Beard *et al.*, (1982). This fit looks quite reasonable down into the Nebraskan stage. My assignment of the two lobes of Oberlin east of the Brazos to high sealevel events Q3 and Q4 is based on the absence of MBR channel preservation on the eastern Oberlin terrace(s) relative to a very little of it on the western one; and on Weeks (1941) report of a poorly developed University terrace between the Asylum (= Lissie) and Capitol (= Oberlin) that I have not recognized along the Brazos, but which is stratigraphically in a position to be equivalent to the Oberlin terrace(s) east of the Brazos. If all this is correct, strata representing all of their Pleistocene high sealevel events could be present at the surface between Texas City and the north line of Harris County. Furthermore, I have tentatively accepted the tripartite division of the conventional Willis Formation suggested by the present investigation and left the two younger "Willis" terraces in the lower Nebraskan stage on the assumption that the sealevel curve for that lengthy interval is incomplete. Also, there is good reason (not presented herein) to believe that a significant unconformity occurs at the top of the very thick, lithologically distinct regolith at the top of my first post-Goliad coastal terrace, referred to herein as "type" Willis. Since this is likely to be closer to the ultimate base of the Pleistocene than the unconformity on top of the Goliad gravelly sands (Figure 9), that is the way it is shown on Figure 8.

Correlation with Geophysical Logs of Shallow Boreholes

Figure 9 is a strike section of shallow resistivity logs from north-central Harris County. This 3150-foot strike line of shallow geophysical borings appears to define the sequences somewhat north of Buffalo Bayou unusually well. The surface formation is definitely Lissie, consisting mostly of clay and silt above a very clean, seemingly transgressive sand near 125 feet, which may be some sort of beach. The other well-defined boundary is the disconformity on top of what I regard as Goliad. This section is characteristically dominated by sands, commonly in upward-fining, almost cyclic units; it is calcareous and often carries siliceous pebbles, mostly of chert, ranging up to one inch in length. The selected Tomball/Willis boundary marks a substantial shift of depositional environments so this is the only practicable place for it. I would expect this "Willis" to be the downdip equivalent of the coastal terrace along the north side of the Tomball terrace, for the next-older terrace to be represented only in the Goliad valleys, and for the oldest terrace (my "type" Willis) to have been cut out here by the unconformity seen on top of the Goliad.

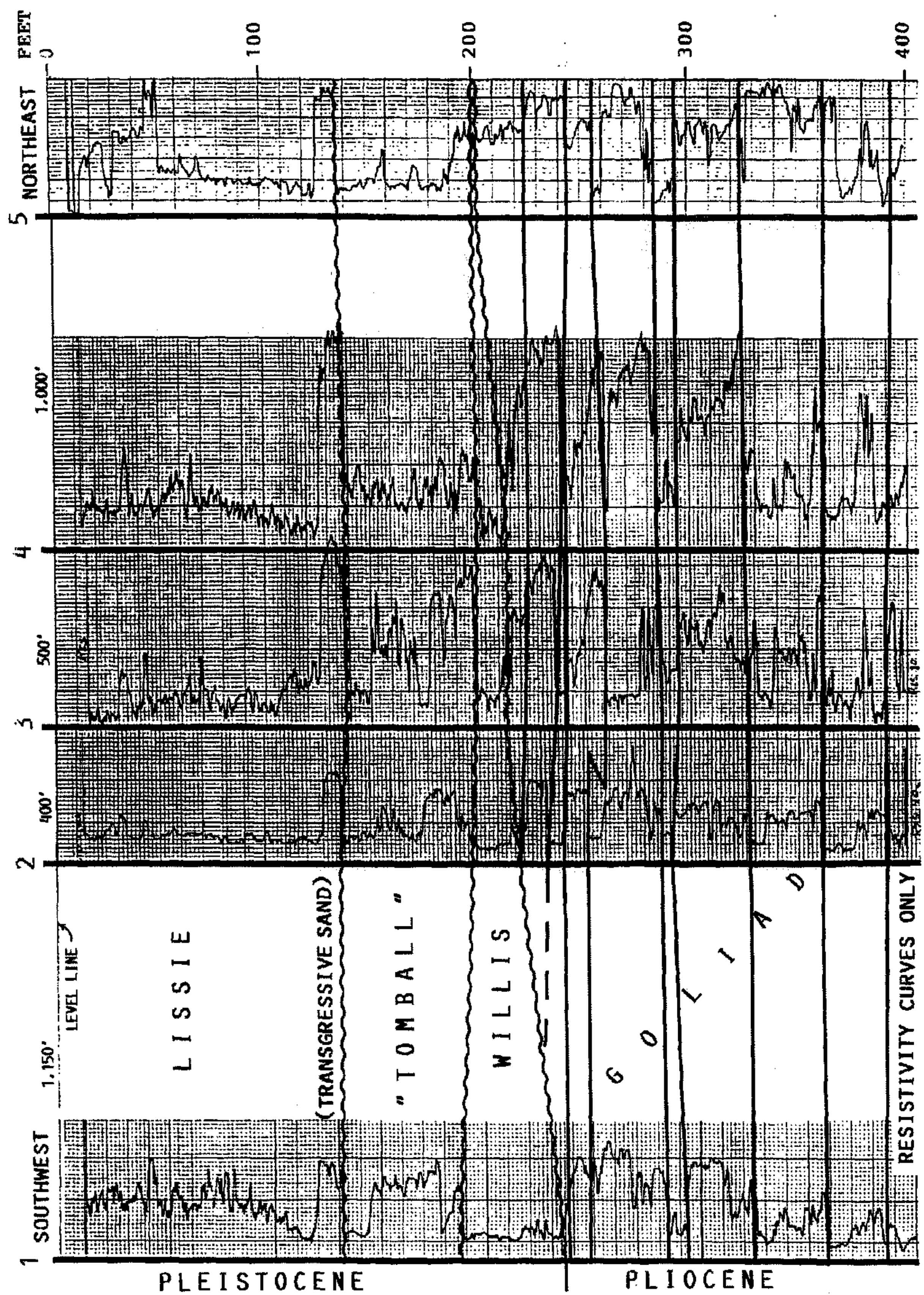

Figure 9. Resistivity–log strike section of Pleistocene strata above buried edge of flat–topped hill of Pliocene Goliad Formation, north–central Harris County, Texas. Wavy lines represent disconformable sequence boundaries; vertical exaggeration is 8 times.

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