Paleomagnetic Core-Orientation Helps Determine the Sedimentological, Paleostress, and Fluid-Migration History in the Maracaibo Basin, Venezuela

David R. Van Alstine and Joseph E. Butterworth
Applied Paleomagnetics, Inc.
Redmond, Washington and Santa Cruz, California, USA
E-mail: api.dva@verizon.net

ABSTRACT

Our 17 years of paleomagnetic work on subsurface cores from hydrocarbon reservoirs in Venezuela demonstrates the benefits of paleomagnetically oriented cores for understanding depositional trends, fracture patterns, and *in situ* stress, with important consequences for permeability anisotropy. Our work has focused on the Maracaibo basin, where we have paleomagnetically oriented cores from Cretaceous (La Luna/Cogollo), Eocene (Misoa), and Miocene (Santa Barbara/La Rosa) reservoirs in the Bachaquero, Ceuta, La Ceiba, Lagunillas, Mara, Sol, and Urdaneta fields, as well as in Bloques I, V, and IX along the Icotea and VLE faults. In eastern Venezuela, we have paleomagnetically oriented cores from the Boqueron, Santa Barbara, and Orocual fields.

In case histories from central Lake Maracaibo, along the Icotea and VLE faults, we illustrate how paleomagnetically oriented cores can be used to calculate structural dip and to determine sediment transport directions in cross-bedded Misoa sandstone reservoirs. In "positive flower structures" along these faults, calculating and correcting for up to 42° of structural dip reveals eastward sediment transport directions in the Misoa C sands. These eastward transport directions may reflect shedding of sediments off the upthrown side of the Icotea and VLE faults during Early Eocene sedimentation.

In case histories from central and eastern Lake Maracaibo, we illustrate how paleomagnetically oriented cores can be used to determine the orientation of face cleats in Misoa Formation coal. This application may become more important in future development of coalbed methane reservoirs in Venezuela, since maximum permeability in coalbed methane reservoirs is generally parallel to the trend of coal cleats.

In case histories from across the Maracaibo basin, we illustrate how paleomagnetically oriented cores can be used to determine the orientation of natural fractures in both carbonate (La Luna/Cogollo) and terrigenous clastic (Misoa) reservoirs. We find that partially open natural fractures generally strike within 45° of being parallel to the direction of present-day *in situ* stress, especially in Cogollo limestone reservoirs. Cores from all 15 Misoa reservoirs we have studied also contain natural fractures. Some Misoa cores contain numerous "deformation bands," which are shear fractures normally considered to be permeability barriers and to compartmentalize reservoirs.

In most cores we have studied from the Maracaibo basin, the *normal-polarity*, present-field magnetization we use to paleomagnetically orient cores has been superimposed on an older, *reversed-polarity* magnetization. This reversed-polarity magnetization is present in all La Luna/Cogollo cores, in Misoa cores (especially reddened, sideritic intervals), and also in La Rosa (Miocene) cores. The reversed-polarity magnetization probably is chemical remanent magnetization (CRM) acquired either during Oligocene uplift or during maximum burial in the past 10 million years. Although the reversed-polarity CRM precludes magnetostratigraphic applications (at least

in the La Luna/Cogollo), understanding the origin and spatial distribution of this remagnetization will probably help determine the diagenetic and fluid-migration history in hydrocarbon reservoirs throughout the Maracaibo basin.

INTRODUCTION

Paleomagnetic core-orientation is a relatively new technique that provides an innovative way to determine the orientation of planar features (bedding and fractures) in subsurface cores. Knowledge of the orientation of bedding and fractures in hydrocarbon reservoirs is important, because bedding and fractures create permeability anisotropy within the reservoirs. Determination of reservoir anisotropy directions is critical for reservoir evaluation and characterization, especially if deviated drilling, hydraulic fracturing, or CO_2 or waterfloods are being considered.

Sedimentation and fracture patterns are best understood in the context of the paleostress history, especially in the Maracaibo basin, which has been subjected to multiple phases of tectonism. Tectonic events that occurred *prior to*, or *during*, sedimentation commonly influence regional sedimentation patterns, sediment transport directions, and the geometry of sand-body reservoirs. Tectonic events that occurred millions of years *after* sedimentation rotate these “primary” depositional bedding features into new orientations in the present-day environment. When working with sedimentary features in subsurface cores, therefore, we must first correctly determine and “unrotate” the structural (tectonic) dip before we can correctly infer the original sediment-transport directions in cross-bedded sandstone. Paleomagnetic orientation of shale bedding and truncation surfaces in cores provides the *most direct* way of determining and correcting for structural dip to reveal original downdip azimuths of primary depositional features.

Reservoir permeability anisotropy reflects a competition between bedding and natural fractures. Natural fractures, including “cleats” in coal, can enhance reservoir permeability if they are open, especially if they are parallel to the present-day *in situ* stress direction (σ_{Hmax}). In contrast, natural fractures can reduce reservoir permeability if they are mineralized or healed.

Paleomagnetically oriented cores can be used to determine the direction of present-day *in situ* stress, by orienting petal and petal-centerline fractures induced during the coring operation. These “induced” fractures generally are good predictors of the orientation of hydraulic fractures, which may be created for reservoir stimulation.

In this paper, we first present some background to our paleomagnetic core-orientation work in Venezuela. We then discuss the scientific basis and procedures used in our paleomagnetic core-orientation technique. We illustrate some paleomagnetic core-orientation applications, using specific examples from our work in the Maracaibo basin. We first present bedding examples where we calculated, and then corrected for, structural dip to reveal sediment transport directions in cross-bedded Misoa sandstones. We then present examples of paleomagnetically-oriented natural and induced fracture patterns, and we consider the paleostress and present-day *in situ* stress fields in which these fractures formed. Finally, we discuss applications of paleomagnetism pertaining to diagenetic and fluid-migration history and potential applications of magnetic stratigraphy.

BACKGROUND TO OUR PALEOMAGNETIC CORE-ORIENTATION WORK IN THE MARACAIBO BASIN

Since 1986, we have been acquiring and interpreting permeability anisotropy data arising from bedding and fractures in Venezuelan hydrocarbon reservoirs, mostly in the Maracaibo basin. Applied Paleomagnetics, Inc. pioneered the paleomagnetic core-orientation technique beginning in 1980. Since then, we have paleomagnetically oriented, measured, and interpreted bedding and fracture patterns in thousands of feet of cores from Venezuela working on projects for PDVSA, Maraven, Lagoven, Intevep, Mobil, Pennzoil, and Shell. Results of some of our early work on La Luna/Cogollo cores from Lake Maracaibo are summarized in Van Alstine et al. (1991) and in Franssen et al. (1992).

In Lake Maracaibo, we have paleomagnetically oriented cores of Cretaceous (Rio Negro, Cogollo, La Luna), Eocene (Misoa C and B), and Miocene (Santa Barbara and La Rosa) age, including both carbonates (limestone and dolomite) and terrigenous clastics (sandstone, siltstone, and shale). In the Maracaibo basin, we have paleomagnetically oriented cores from the Bachaquero, Ceuta, La Ceiba, Lagunillas, Mara, Sol, and Urdaneta fields, as well as from Bloques I, V, and IX along the Icotea and VLE faults in central Lake Maracaibo. In eastern Venezuela, we have paleomagnetically oriented cores from the Boqueron, Santa Barbara, and Orocual fields.

SCIENTIFIC BASIS OF THE PALEOMAGNETIC CORE ORIENTATION TECHNIQUE

Contrary to much of what appears in the literature (e.g., Davison and Haszeldine, 1984; Nelson et al., 1987) about paleomagnetic core orientation, we do not normally orient cores to any “primary” magnetization acquired near the time of deposition. If a primary magnetization were used to orient cores, it would be necessary to know the precise age of the rock, the reference “apparent polar wander path,” and the structural attitude, all of which are commonly unknown.

Instead, we paleomagnetically orient cores using a “secondary” magnetization referred to as present-axial-dipole field (PADF) viscous remanent magnetization (VRM). Present-field VRM, which is ubiquitous in drillcores from throughout the world, generally resides in “multi-domain” magnetite (Fe_3O_4) coarser than about 10 or 15 µm. Magnetite of this grain-size is present in nearly all rocks, including carbonates at ppm concentrations, and cannot retain remanent magnetization over time scales longer than 10^6 years. PADF VRM, which points to present-day geographic north, represents a time-average of the geomagnetic field over the past 780,000 years, which is the time since the last geomagnetic polarity “reversal.” The advantages of using present-field VRM for paleomagnetically orienting subsurface cores were first recognized 32 years ago (Fuller, 1969).

In the paleomagnetic laboratory, “progressive thermal demagnetization” is employed to identify and separate multiple components of magnetization that may reside in individual paleomagnetic specimens. This technique consists of first measuring the natural remanent magnetization (NRM) of the specimens and then subjecting them to thermal demagnetization in 5 or 6 steps between 100° and 300°C; the magnetic remanence is remeasured after each demagnetization step. Measurements of remanent magnetization are made using a computerized, superconducting (SQUID) magnetometer in a magnetically shielded room. In calculating paleomagnetic core orientations, the thermal demagnetization data are statistically processed using principal component analysis (Kirschvink, 1980) to isolate the direction of the PADF VRM signal that points to present-day geographic north.

Since present-field VRM is acquired more readily at higher temperatures, orienting cores using VRM means that the paleomagnetic core-orientation technique actually works better with increasing core depth, unlike conventional and electronic "multishot" and other downhole tools that are affected by high bottomhole temperatures. Once cores have been brought to the surface, the present-field VRM signal can survive room-temperature storage for thousands of years. Thus, cores that have been in storage for decades can still be paleomagnetically oriented to reveal fracture and bedding patterns contributing to reservoir permeability anisotropy.

PALEOMAGNETIC CORE-ORIENTATION PROCEDURES

In paleomagnetically orienting cores, we first reconstruct the core into "continuous intervals," which we define as the longest intervals of core that can be reliably reconstructed by fitting adjacent pieces. Next, we draw a Master Orientation Line (MOL) on the core using an angled-aluminum straight-edge (Figure 1, Step 1). Finally, we drill a series of 1-inch (2.5 cm) diameter plugs at precise angles relative to the MOL. These plugs are drilled using a non-magnetic plugging bit inside a portable magnetic shield.

For high orientation accuracy, we normally drill 6 to 8 paleomagnetic plugs per continuous interval and subsequently cut each plug into two 11 cm^3 "specimens." As shown in Figure 1 (Step 2), half of the plugs (designated "non-Z plugs") are drilled into the MOL, and the other half of the plugs (designated "Z plugs") are drilled along a "Z line" at a known 180° angle to the MOL.

We designed this "antiparallel plug technique" in the early 1980s, for use on the U.S. Department of Energy's Multi-Well Experiment (MWX) in Mesaverde tight gas sands of the Piceance Basin (Van Alstine and Gillett, 1982). Analyzing the distributions of paleomagnetic directions from "Z" and "non-Z" plugs allows us to recognize and mathematically eliminate any spurious "secondary" magnetization acquired during plugging. After rotating paleomagnetic directions from Z plugs by the known 180° plugging angle, the vector *sum* of the Z/non-Z distributions is the unbiased geophysical remanence vector, and the vector *difference* is the "deflection vector" acquired during plugging.

Since 1980, we have continued to test and refine our paleomagnetic core-orientation technique in orienting over 16,000 feet of core from around the world (Bleakly et al., 1985a, b; Van Alstine et al., 1991; Van Alstine and Butterworth, 1993; Hamilton et al., 1995, 1996; Vasquez et al., 1999).

OVERVIEW OF PALEOMAGNETIC DATA FROM MARACAIBO BASIN CORES

Figure 2 illustrates typical paleomagnetic data we obtain from Eocene (Misoa) and Cretaceous (La Luna/Cogollo) cores from the Maracaibo basin. As shown in this figure, paleomagnetic directions from the separate "Z" (red triangles) and "non-Z" (blue dots) distributions are tightly clustered and nearly 180° apart (i.e., the known 180° angle between "Z" and "non-Z" plugs). This demonstrates that the paleomagnetic MOL orientations are not biased by any artifact of the plugging operation

As in other paleomagnetic studies we have conducted around the world, the strongest paleomagnetic signal in most cores from the Maracaibo basin exhibits "normal polarity" (i.e., points downward). This normal-polarity magnetization undoubtedly represents the present axial dipole field (PADF) viscous remanent magnetization (VRM) we normally use as the "reference direction" in our paleomagnetic core-orientation projects around the world.

In Venezuela, we have been equally successful in paleomagnetically orienting both fresh (whole) and archived (slabbed) cores with diameters typically either 4 inches (10.2 cm) or 2.6 inches (6.6 cm). Most of the sampled “continuous intervals” were long enough to permit a full suite of our recommended 6 plugs (12 specimens) per interval. This paleomagnetic sample density is generally adequate to ensure paleomagnetic orientation accuracy to within 5°.

Below, we consider the implications of these paleomagnetic orientations regarding bedding and fracture patterns and their implications for reservoir permeability anisotropy.

PALEOMAGNETIC ORIENTATION OF BEDDING TO DETERMINE SEDIMENT TRANSPORT DIRECTIONS AND STRUCTURAL DIP IN CORES FROM THE MARACAIBO BASIN

Figure 3 illustrates why it is so important to first determine, and then correct for, structural dip before inferring sediment transport directions from Maracaibo basin cores. In the Maracaibo basin, many wells are drilled into anticlinal features developed in “positive flower structures” and “restraining bends” along transpressional faults, such as the Pueblo Viejo, VLE, Icotea, and Mara faults. Although the Figure 3 cross-section shows the idealized “positive flower structure” discussed by Christie-Blick and Biddle (1985), it perfectly illustrates the structural dips we paleomagnetically determined in Eocene (Misoa C2 through C5) cores from Bloque V wells VLE-1063 and VLE-1254. These two wells are just east of the VLE fault, which is a major transpressional fault east of the Icotea fault in central Lake Maracaibo.

As shown in Figure 4, the structural dip angle in VLE-1063, which is closer to the center of the flower structure, is 25°. As shown in Figure 5, the structural dip angle in VLE-1254, farther on the flank of the flower structure, decreases gradually with depth from a high of 42° to a low of 30°. An intraformational unconformity occurs near 12,092 ft in this well, but it is recognized primarily by a change in downdip azimuth (118° to 133°) rather than by a change in dip angle (32° to 30°).

Only after determining and correcting for the 25° to 42° structural dip in these wells can we correctly infer the eastward (VLE-1254) and northeastward (VLE-1063) sediment transport directions, which are indicated in rose diagrams at the lower right in Figures 4 and 5. The structural dip can be determined by carefully identifying shale bedding and truncation surfaces in these fluvial-deltaic deposits, a task which is most easily achieved by close inspection of cores. In contrast, other less direct methods, such as dipmeter surveys and image logs, commonly lack the resolution to distinguish between shale bedding and truncation surfaces versus cross-bedding. This can yield inaccurate structural dip values and inaccurate sediment transport directions.

Figure 6 illustrates a paleomagnetic core-orientation example where the structural dip angle is much lower (4°) in well VLA-1321. This well, in Bloque I, is near the crest of a domal feature along the Icotea fault. After correcting for the 4° structural dip, we can again infer an eastward sediment transport direction in these Eocene (Misoa C4) sands.

Figure 7 provides one possible explanation for the easterly sediment transport directions we infer from paleomagnetically oriented Misoa C cores in central Lake Maracaibo. In this model, the easterly sediment transport directions reflect the wellsite locations on the structurally upthrown, east side of the Icotea and VLE faults. These were active normal faults in the Early Eocene, when the Misoa C sands were deposited (Ghosh et al., 1996).

Figure 8 provides another possible explanation for the easterly sediment transport directions we infer from paleomagnetically oriented Misoa C cores in central Lake Maracaibo. All three of these wells (VLE-1063, VLE-1254, and VLA-1321) are on the east sides of anticlines formed between the Icotea and VLE faults or between the Icotea and Lama faults. Figure 8 suggests that sometime between deposition of the Misoa C5 and C4, the regional σ_{Hmax} might have shifted from the 28° value in the Early Eocene (promoting NNE sediment transport) to the 116° value that prevailed later in the Eocene. This 116° paleostress direction would have promoted both transpression along the Icotea/Lama/VLE fault system and development of the numerous ESE-trending, down-to-the-north cross-faults shown in Figure 8.

Regardless of which interpretation is correct, this example illustrates how paleomagnetically oriented cores can help "see through" a complicated post-depositional structural history in order to infer primary depositional trends.

PALEOMAGNETIC ORIENTATION OF COAL CLEATS IN CORES FROM THE MARACAIBO BASIN

Many of the Misoa cores we have paleomagnetically oriented contain thin coal seams, commonly formed in organic drapes on cross-beds in sandstone. These coal seams commonly exhibit a well-developed orthogonal system of "face and butt cleats." Face cleats are essentially small-scale extension joints striking parallel to the paleostress field in which they formed. Face cleats commonly strike perpendicular to orogens (i.e., ⊥ to thrust faults) in foreland basins (cf. Kulander and Dean, 1993). In coal, a less systematic, nearly orthogonal set of fractures is referred to as "butt cleats," presumably because they abut or "butt" against face cleats at nearly a 90° angle. Butt cleats are generally thought to reflect relaxation of the paleostress field in which face cleats formed, and butt cleats can develop during post-orogenic isostatic uplift.

Establishing coal cleat orientations is especially important in coalbed methane reservoirs. Enhanced permeability is commonly observed along the trend of whichever cleat set (face or butt) is closest to (and hence held open by) the present-day *in situ* stress field. Development of coalbed methane reservoirs may become increasingly important in Venezuela (Vasquez et al., 1996).

Figure 9 summarizes our paleomagnetic orientations of face cleats in Misoa Formation coal seams and shale. We find that Misoa shales commonly exhibit orthogonal joint sets that are parallel to face and butt cleats in cores in which both shale and coal are present. As revealed in Figure 9, the paleomagnetically oriented face-cleat azimuths from east-central Lake Maracaibo are contained within an 80°-wide arc which is bisected by an azimuth of 28°. In any given well, the face cleat orientations are locally deflected to be parallel or perpendicular to the nearest major fault.

The 28° azimuth in Figure 9 is essentially the same as the regional paleostress direction inferred for east-central Lake Maracaibo during development of the Paleocene to Middle Eocene thrust belt (Figure 7). In two wells (BA-622 and VLG-3815), face cleats are parallel to high-angle (steeply dipping) natural *extension* fractures, and face cleats are ⊥ to low-angle (shallow dipping) natural *shear* fractures. This further implies that face cleats in Misoa coal and shale developed as a consequence of Eocene thrusting and are associated with what Lugo (1991) calls "distal thrusts of the foreland basin"which extend nearly to central Lake Maracaibo (Figure 9).

In summary, paleomagnetically-oriented face cleats in Misoa coal and shale probably formed in the waning stages of Eocene thrust faulting, when the Misoa was at its maximum thickness prior to erosion of thousands of feet of Eocene strata during Oligocene uplift (cf. Bockmeulen et al., 1983).

PALEOMAGNETIC ORIENTATION OF NATURAL FRACTURES IN CORES FROM THE MARACAIBO BASIN

Natural Fractures in Cretaceous Reservoirs

In the Maracaibo basin, many Cretaceous (La Luna/Cogollo) reservoirs are "fractured reservoirs," meaning that fractures probably exert the greatest control on reservoir permeability anisotropy. The types of fractures that occur in La Luna/Cogollo cores from Lake Maracaibo have been described by Franssen et al. (1992), based on our paleomagnetic core-orientation work in SVS-225 and SVS-229 along the Icotea fault.

Figures 10 and 11 illustrate typical examples of paleomagnetically oriented natural fractures in Cogollo Group (Apon Formation) cores from the Maracaibo basin. These examples show two of the three fracture sets we commonly observe in Cretaceous cores from this region. We designate the SE-striking fractures as "Set 1," because they are generally the most well-developed fracture set in each well. We designate the NNE-striking fractures as "Set 2." A third set (not shown) is designated "Set 3," exhibits ENE strikes, and is less well-developed in the Maracaibo basin than are Set 1 and Set 2 fractures.

The fracture patterns in Figure 10 emphasize how major faults in the Maracaibo basin commonly act as "stress guides" to deflect regional stresses into nearly fault ⊥ configurations. This phenomenon has also been observed along the San Andreas fault in southern California (Zoback et al., 1987).

The geographic distribution of Set 2 fractures relative to the Paleocene-Eocene thrust belt (Figure 11) suggests that Set 2 fractures are *extension* fractures formed by regional compression in the foreland of the Paleocene-Eocene thrust belt, when the paleostress direction was oriented NNE. Set 1 fractures, which are commonly *shear* fractures, probably formed during Eocene and Miocene transpression, when the regional paleostress direction was oriented SE to ESE.

Natural Fractures in Eocene Reservoirs

Although Eocene (Misoa) reservoirs in the Maracaibo basin are not normally thought of as "fractured reservoirs," every Misoa core from the 15 wells we have paleomagnetically oriented contains natural fractures which probably contribute to permeability anisotropy.

Figure 12 shows typical natural fracture patterns we observe in paleomagnetically oriented cores of the Misoa Formation from east-central Lake Maracaibo. As in La Luna/Cogollo cores, Misoa cores also contain ESE-striking Set 1 fractures, NNE-striking Set 2 fractures, and (more rarely) ENE-striking Set 3 fractures.

Figure 12 nicely illustrates that *fractures* in paleomagnetically-oriented Misoa cores are nearly parallel to *faults* in seismically-derived structural maps. Moreover, most of the Set 1 and Set 2 fractures shown in Figure 13, from VLE-1063, are a type of shear fracture known as "deformation bands." Faults and shear fractures are known to exhibit "fractal" relationships (Loosveld and Franssen, 1992), which is probably why fault and fracture patterns in Misoa reservoirs are so similar (e.g., Figure 12).

The Set 1 and Set 2 "deformation bands" in Figure 13 are, to our knowledge, the first reported occurrence of deformation bands in Eocene reservoirs in the Maracaibo basin. Deformation bands have been widely studied in sandstones from North America (Antonellini and Aydin, 1994, 1995). Deformation bands are notorious for "compartmentalizing" hydrocarbon reservoirs, because each mm-thick band commonly forms by cataclasis (Loosveld and Franssen, 1992). Hence, deformation bands generally represent barriers to fluid flow.

Within any given Misoa reservoir, therefore, permeability anisotropy will probably be controlled both by sedimentological (sediment transport, sand-body geometry) and by structural (fractures, faults, and structural dip) influences.

PALEOMAGNETIC ORIENTATION OF INDUCED FRACTURES IN CORES FROM THE MARACAIBO BASIN

Nearly all Cretaceous and Eocene cores we have paleomagnetically oriented from the Maracaibo basin contain drilling induced fractures, which are created during the drilling and coring operation. As shown in Figure 14, induced fractures generally propagate ahead of the core bit, and induced fractures strike parallel to present-day *in situ* stress. Paleomagnetically oriented induced fractures have the following two practical applications:

- Predict the strike of hydraulic fractures.
- Predict whether natural fractures will remain open during production.

Based on our paleomagnetically oriented induced fractures in about 25 wells from the Maracaibo basin, we find that *in situ* stress in Cretaceous and Eocene reservoirs is heterogeneous, although understandable. Any simple concept of some single governing *in situ* stress direction, such as Andean orogeny 90°, is invalid, because this far-field stress is being superimposed on pre-existing geomechanical anisotropies originating from the following three sources:

- Deflection (by up to ±45°) of Andean orogeny far-field stress in wells within a few km of major faults (Icotea, VLE, Pueblo Viejo, Mara). We call this "Category 1" *in situ* stress, as illustrated in Figure 15.
- "Bending anisotropy" and "tangential longitudinal strain" that cause *in situ* stress in competent, *sandy* lithologies to be aligned with fold axes (i.e., orthogonal Set 1/Set 2 fractures) in wells near fold crests. We call this "Category 2" *in situ* stress, as illustrated in Figure 16.

- Eocene cleat fabrics in less competent, *shaly* lithologies, such as preferentially seen in wellbore breakout data. We call this "Category 3" *in situ* stress (not illustrated).

PALEOMAGNETIC CONSTRAINTS ON DIAGENETIC AND FLUID-MIGRATION HISTORY IN CORES FROM THE MARACAIBO BASIN

Paleomagnetic samples we have analyzed from the Maracaibo basin generally contain two superimposed magnetizations, as follows:

- The recently-acquired, *normal-polarity* PADF VRM that we use as the "reference magnetization" in paleomagnetically orienting cores to present-day North.

- An older, *reversed-polarity* magnetization that probably represents chemical remanent magnetization (CRM) acquired by growth of new magnetic minerals during diagenetic or fluid-migration events involving hydrocarbons.

Thus, as a byproduct of our paleomagnetic core-orientation technique, we generally obtain additional paleomagnetic data with two potential applications:

- If the older magnetization can be shown to be "primary" (i.e., depositional remanent magnetization, DRM, acquired at the time of deposition) then "magnetostratigraphic" applications are possible. This allows precise age-dating of a formation by comparison with the known geomagnetic polarity time scale (Ogg, 1995; see black-white stripes at bottom of Figure 17).

- If the older magnetization can be shown to be "secondary" (i.e., imposed by chemical or thermal processes 10^7 to 10^8 years after deposition), then paleomagnetism can be used to constrain the timing of fluid-migration and diagenetic events (cf. Van Alstine and Butterworth, 1994; Van Alstine et al., 1997). For example, new magnetic minerals are created during dolomitization, oxidation of siderite or pyrite, maturation of hydrocarbons, and the smectite-to-illite clay-mineral transformation.

In our early paleomagnetic core-orientation projects in the Maracaibo basin, in the mid 1980s to early 1990s, we first became aware that Cogollo and La Luna cores nearly always contain a reversed-polarity magnetization, in addition to the normal-polarity PADF VRM we use to orient the cores. Close inspection of Figure 17 reveals that the reversed-polarity magnetization in the La Luna/Cogollo *cannot* be a primary magnetization (DRM), because the La Luna and Cogollo are known to have been deposited during the "Cretaceous Normal-Polarity Superchron," during which the geomagnetic field consistently exhibited normal polarity (no reversals) for 35 million years between 118 and 83 Ma. Thus, the reversed-polarity magnetization in the La Luna/Cogollo must be a "secondary" magnetization, which precludes magnetostratigraphic applications in these formations.

When we subsequently began to perform paleomagnetic core-orientation projects in Eocene (Misoa Formation) reservoirs of the Maracaibo basin, in the mid 1990s to present, we were surprised to discover that this same reversed-polarity, probably "secondary" magnetization is also generally present in Misoa cores. The reversed-polarity magnetization in Misoa cores is especially strong in reddened or rusty-colored intervals, which probably reflect growth of new magnetic iron oxides, such as maghemite (γFe_2O_3) and hematite (αFe_2O_3), as a result of siderite oxidation.

Figure 17 reveals that the secondary, reversed-polarity magnetization in the Cogollo, La Luna, and Misoa was probably acquired either during the “middle Tertiary reversed-polarity bias interval” (38 to 25 Ma, late Eocene to late Oligocene) or during the “late Cenozoic reversed-polarity bias interval” (past 10 million years).

Acquisition of the reversed-polarity secondary magnetization in the Oligocene is geologically reasonable, because it could be associated with the major uplift that affected central Lake Maracaibo, resulting in erosion of thousands of feet of Misoa strata.

Acquisition of the reversed-polarity secondary magnetization in the past 10 million years is also geologically reasonable, because it would be associated with diagenetic and chemical changes that occurred during maximum burial.

Recently, we discovered a strong reversed-polarity magnetization in Miocene (La Rosa Formation) cores from central Lake Maracaibo, suggesting that the late Cenozoic remagnetization age is more likely.

Further paleomagnetic work on cores will reveal the origin and significance of this reversed-polarity magnetization and its importance in understanding the diagenetic and fluid-migration history of the Maracaibo basin.

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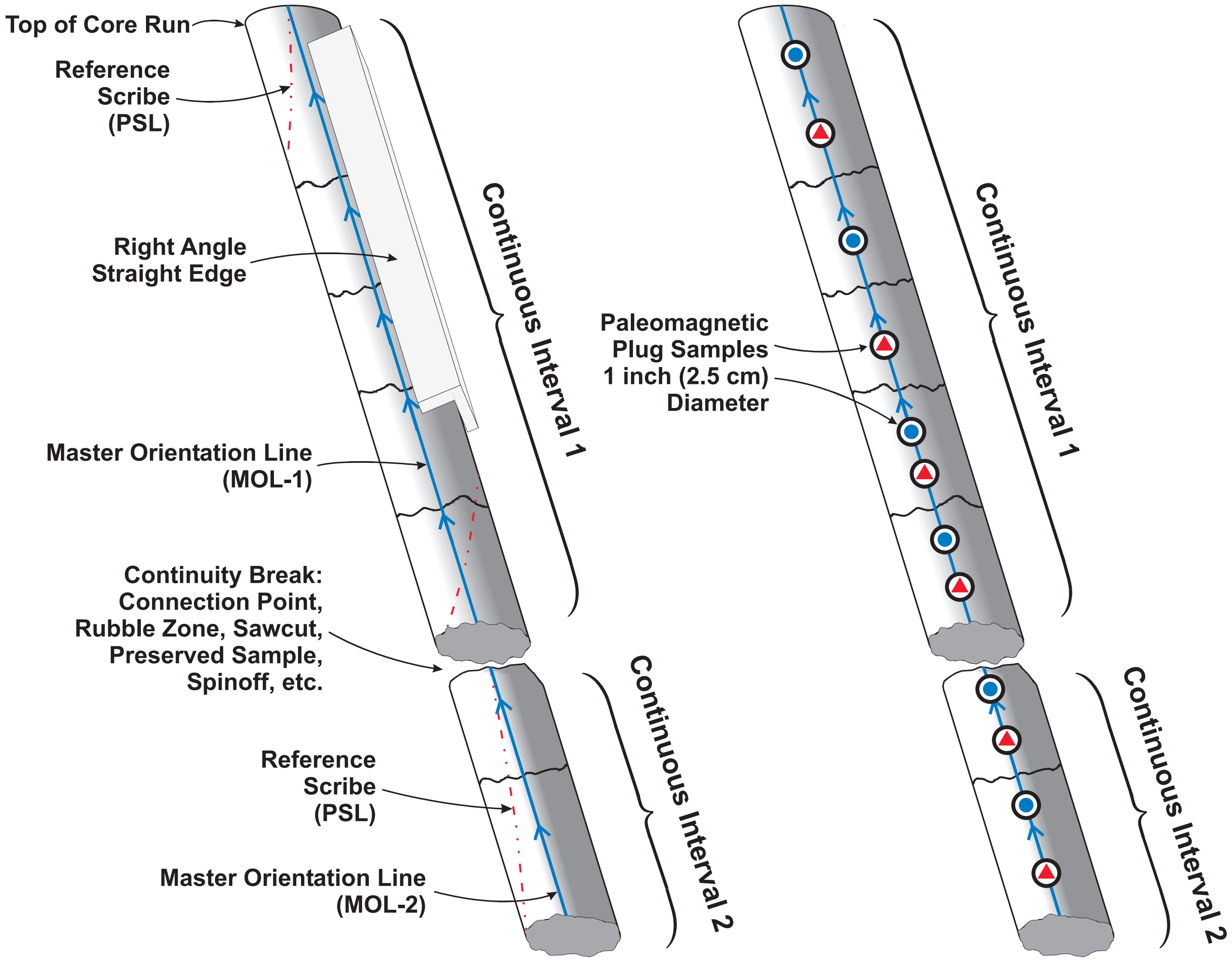
Methodology of the Paleomagnetic Core-Orientation Technique



Step 1. Reconstruct the core into "continuous intervals" and mark the "Master Orientation Line" (MOL). Note that the MOL is a known straight line. In contrast, the Principal Scribe Line (PSL) rotates relative to the MOL. The PSL is only present if the core has been oriented by multishot.

Step 2. Drill a suite of paleomagnetic plugs using the "antiparallel plug technique." Half the plugs (blue dots) are drilled into the MOL, and the other half of the plugs (red triangles) are drilled opposite the MOL.

Figure 1. Methodology of the paleomagnetic core-orientation technique as developed by Applied Paleomagnetics, Inc.

Typical Paleomagnetic Core-Orientation Data from Cretaceous (Cogollo) and Eocene (Misoa) Cores from the Maracaibo Basin

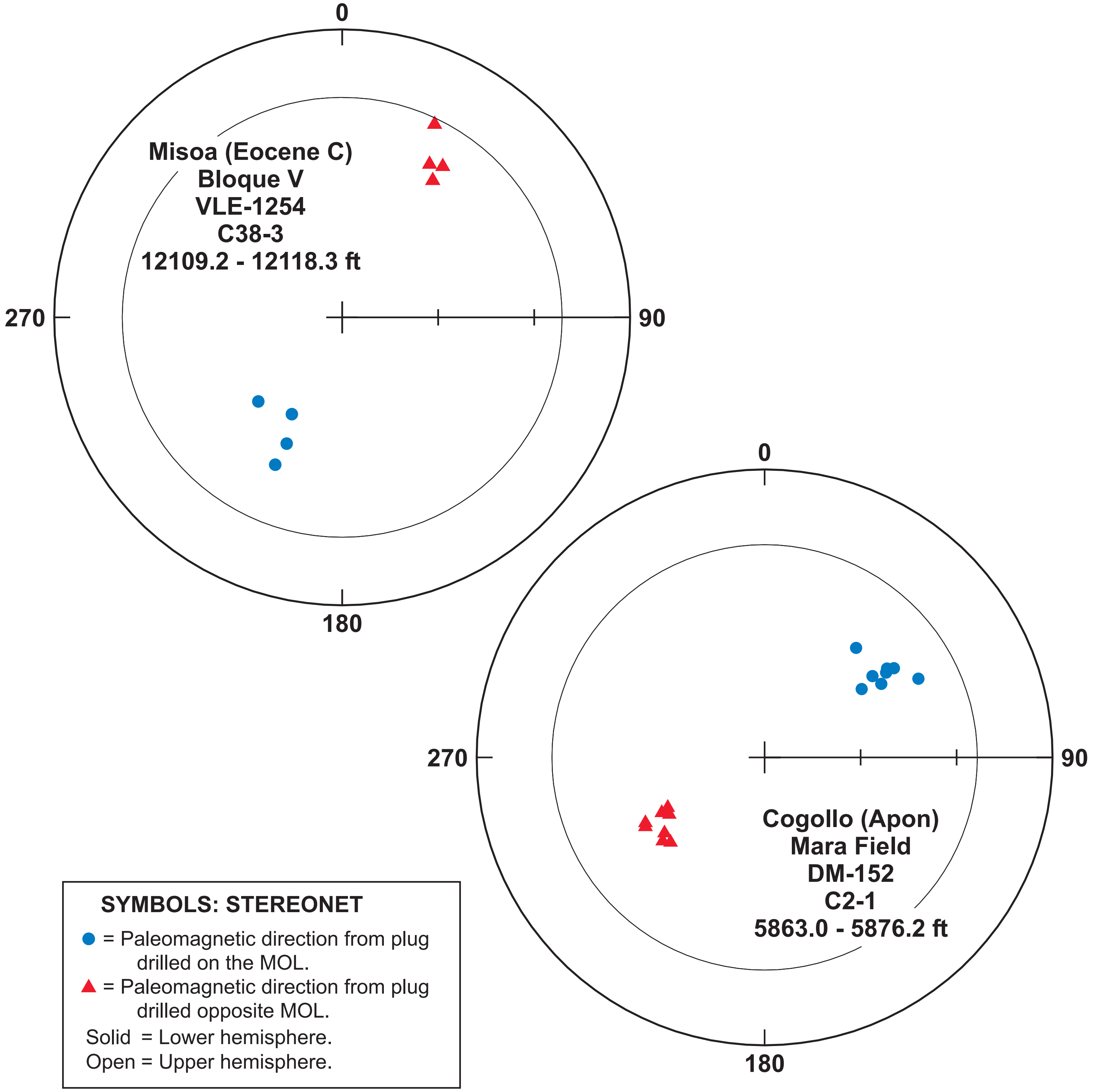


Figure 2. Distributions of paleomagnetic directions used to paleomagnetically orient two typical "continuous intervals" of Eocene (top) and Cretaceous (bottom) cores from the Maracaibo basin. Declination = 0° points toward the Master Orientation Line (MOL).

Structural Setting of Bedding & Fractures in VLE-1063 & VLE-1254

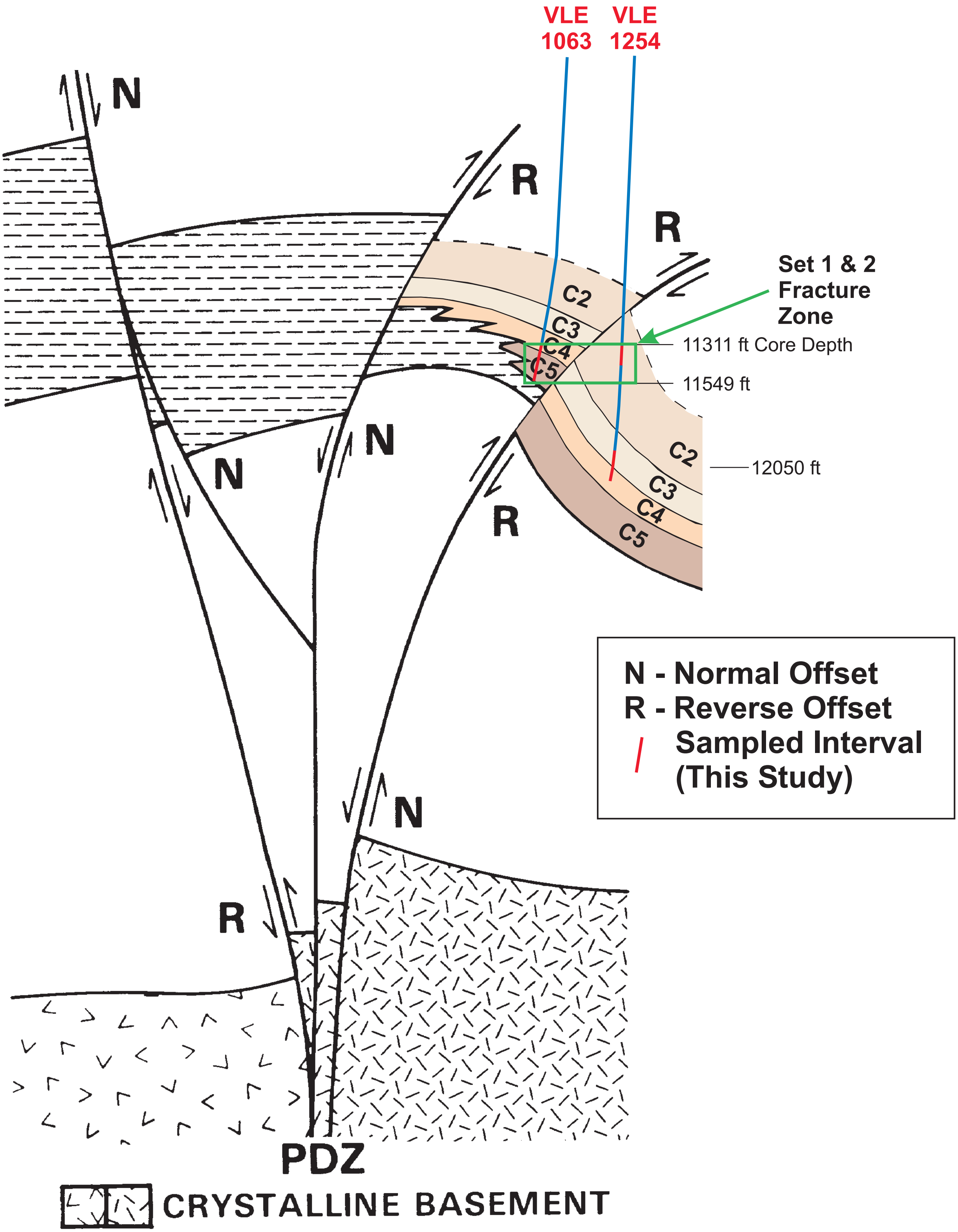
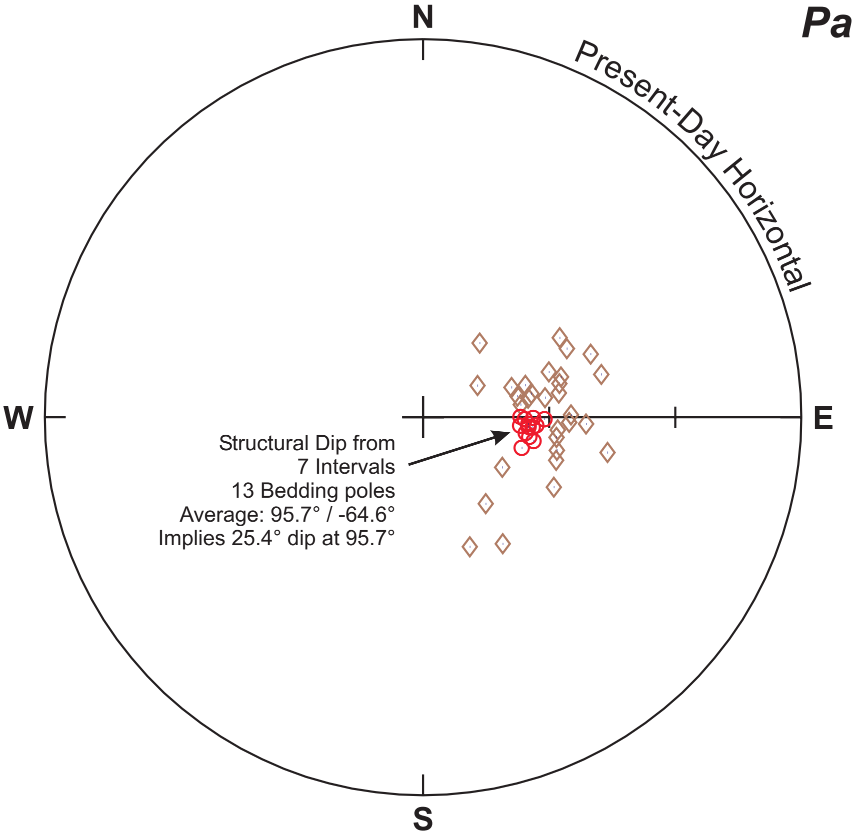


Figure 3. In VLE-1063 and VLE-1254, bedding and fracture orientations are strongly influenced by the structural location in a "positive flower structure" along the VLE fault. The cross-section of an idealized positive flower structure along a strike-slip fault is from Christie-Blick and Biddle (1985).

Paleomagnetically Oriented Bedding
VLE-1063
Cores 1 thru 6
11306.7 - 11548.9 ft
Eocene C4 & C5



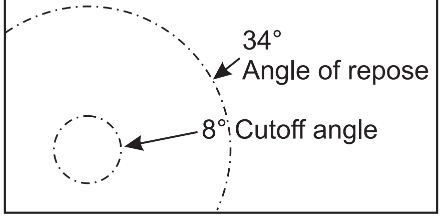
Structural Dip from
7 Intervals
13 Bedding poles
Average: 95.7° / -64.6°
Implies 25.4° dip at 95.7°

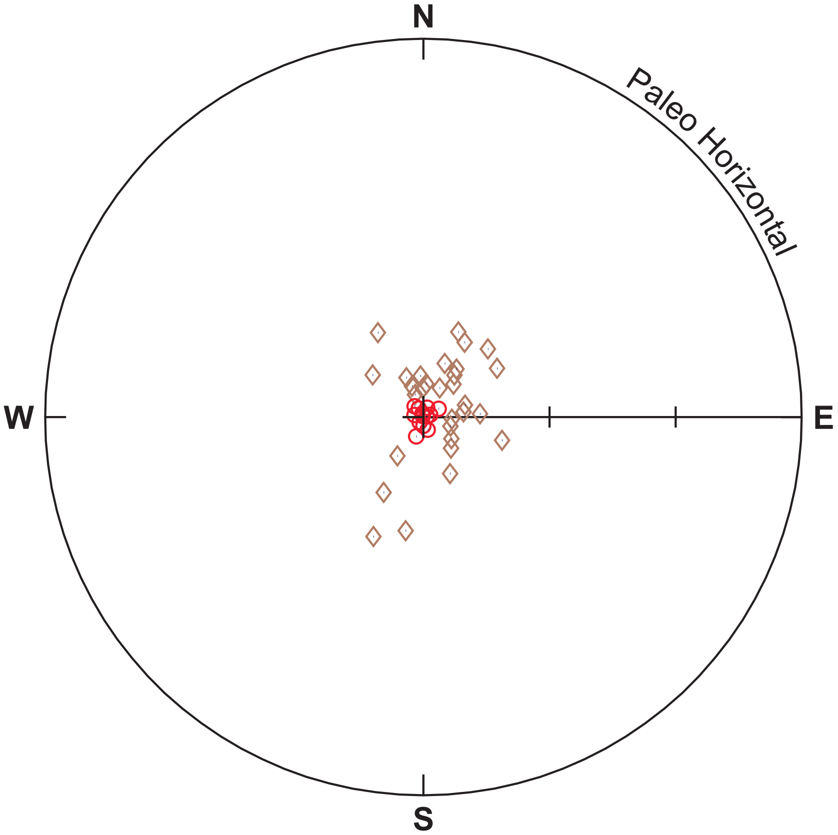
EXPLANATION

○ = Pole to shale bedding & truncation surfaces (structural dip).

◇ = Pole to sandy/silty bedding (sediment transport).

Open = Upper hemisphere (downdip azimuths).





Sediment Transport Directions

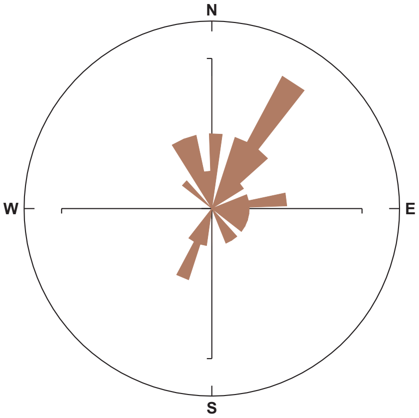


Figure 4. Paleomagnetically oriented poles to 43 bedding planes in Eocene cores from well VLE-1063. Top = “geographic coordinates” before correcting for structural dip. Bottom = “stratigraphic coordinates” after correcting for structural dip. Bottom right = sediment transport directions inferred from high-angle bedding (diamonds).

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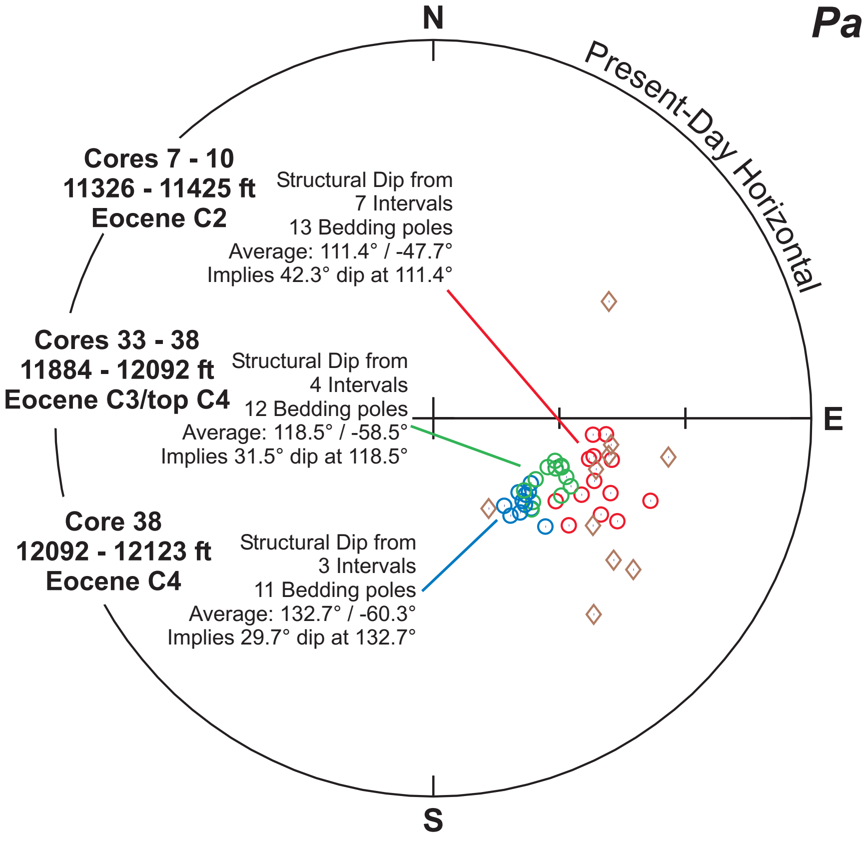
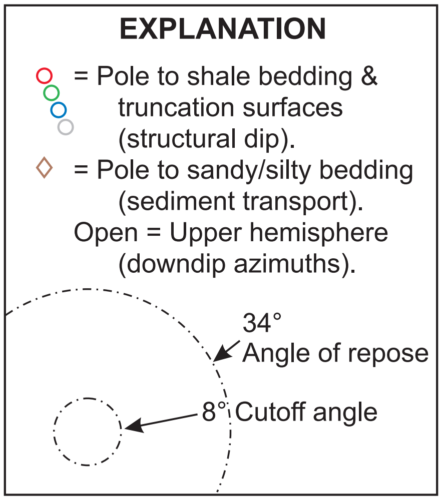
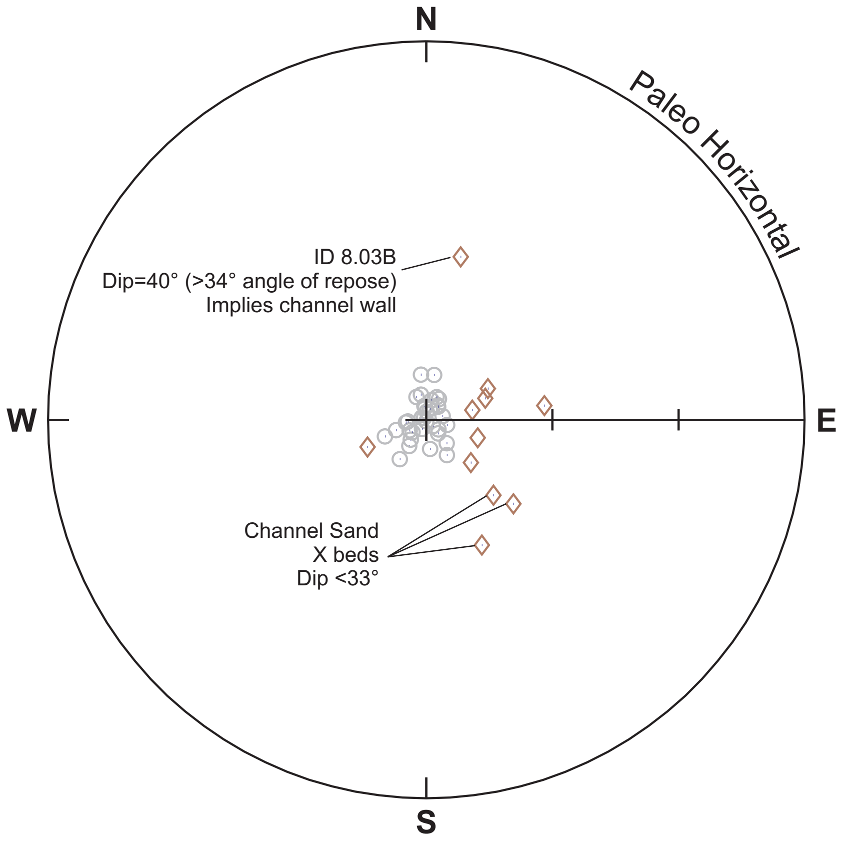
Paleomagnetically Oriented Bedding
VLE-1254
Cores 7 thru 38
11326.0 - 12123.6 ft
Eocene C2, C3, C4







Sediment Transport Directions

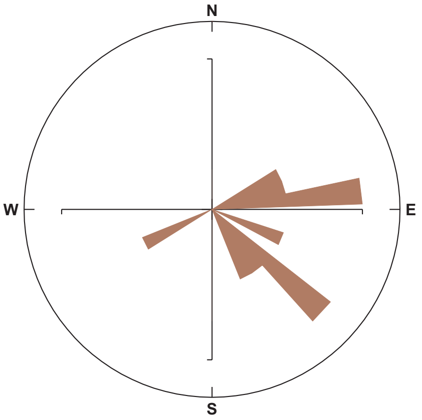
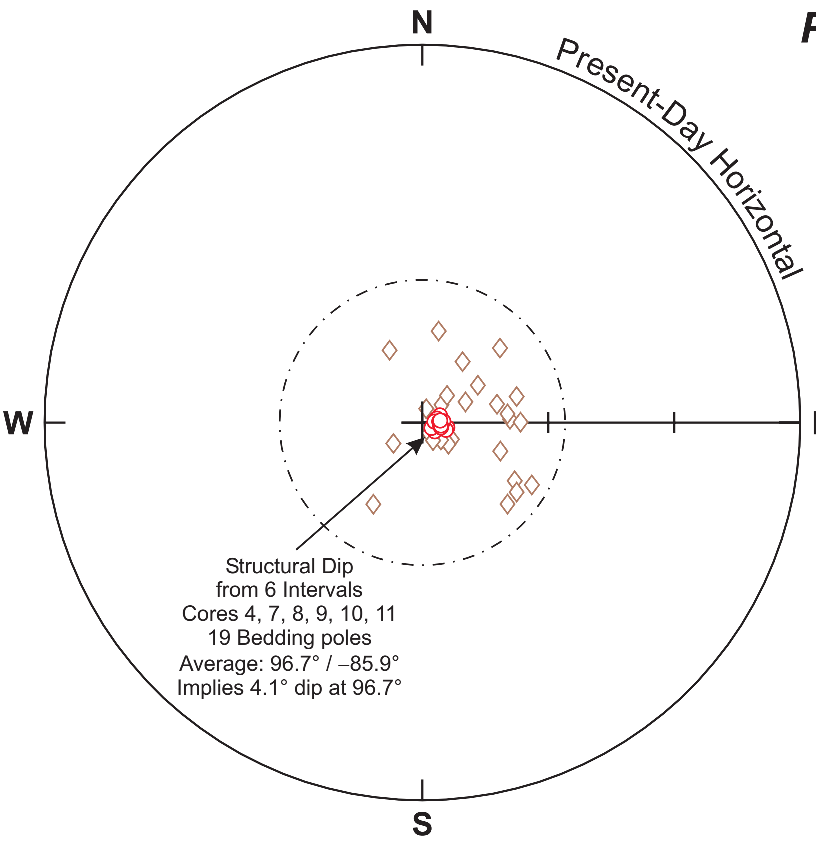
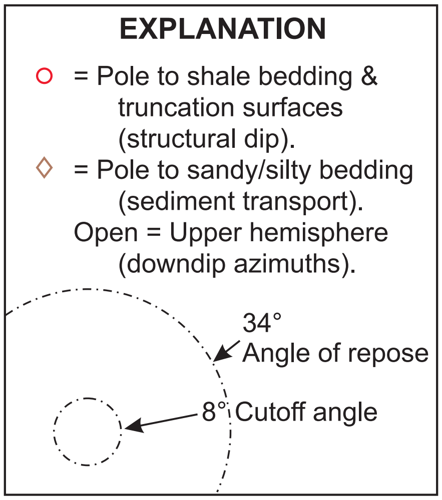
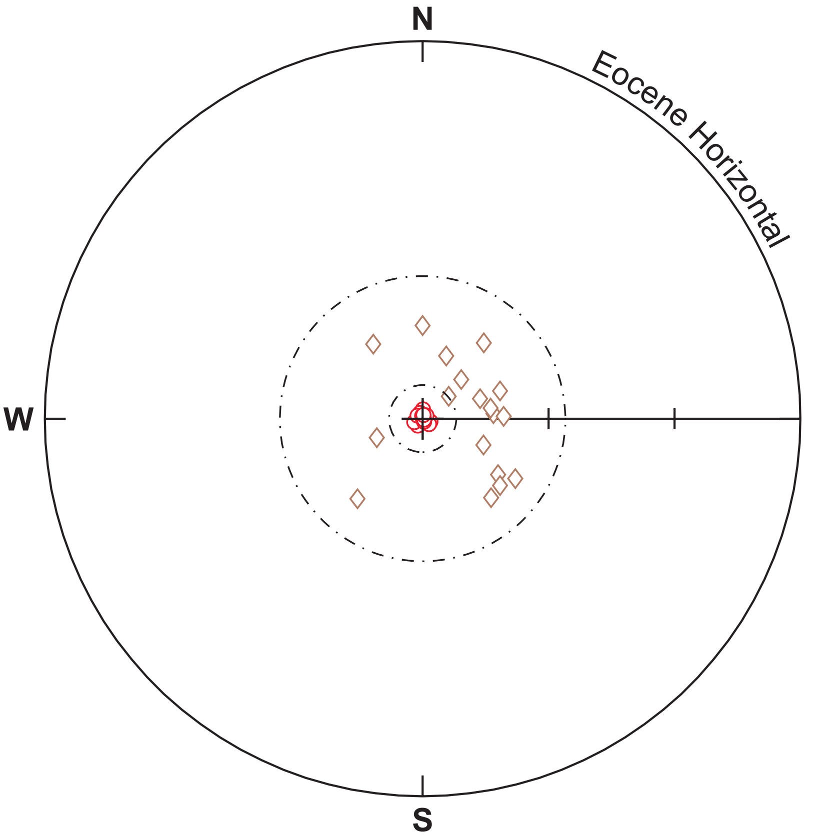


Figure 5. Paleomagnetically oriented poles to 46 bedding planes in Eocene cores from well VLE-1254. Top = "geographic coordinates" before correcting for structural dip. Bottom = "stratigraphic coordinates" after correcting for structural dip. Bottom right = sediment transport directions inferred from high-angle bedding (diamonds). Note the decreasing structural dip angle with depth, as predicted in Figure 3.

Paleomagnetically Oriented Bedding
VLA-1321
Cores 4, 6, 7, 8, 9, 10, 11
5669.0 - 5951.1 ft
Eocene C4







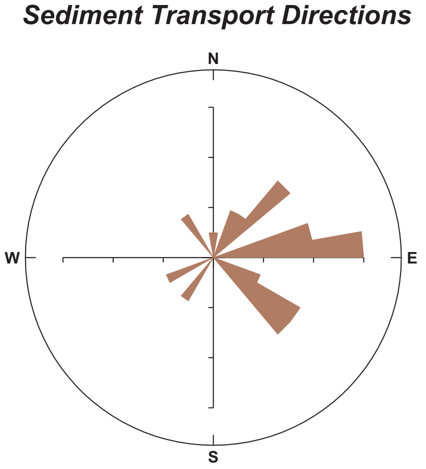


Figure 6. Paleomagnetically oriented poles to 47 bedding planes in Eocene C4 cores from well VLA-1321. Top = "geographic coordinates" before correcting for structural dip. Bottom = "stratigraphic coordinates" after correcting for structural dip of 4.1° at 96.7°. Bottom right = sediment transport directions inferred from the 18 high-angle bedding poles (diamonds) dipping >8° relative to the Eocene horizontal.

Explanation of the Easterly Sediment Transport Directions in Misoa C3/C4/C5 in Central Lake Maracaibo by Rivers Flowing off the East, Upthrown Side of the Icotea and VLE Faults

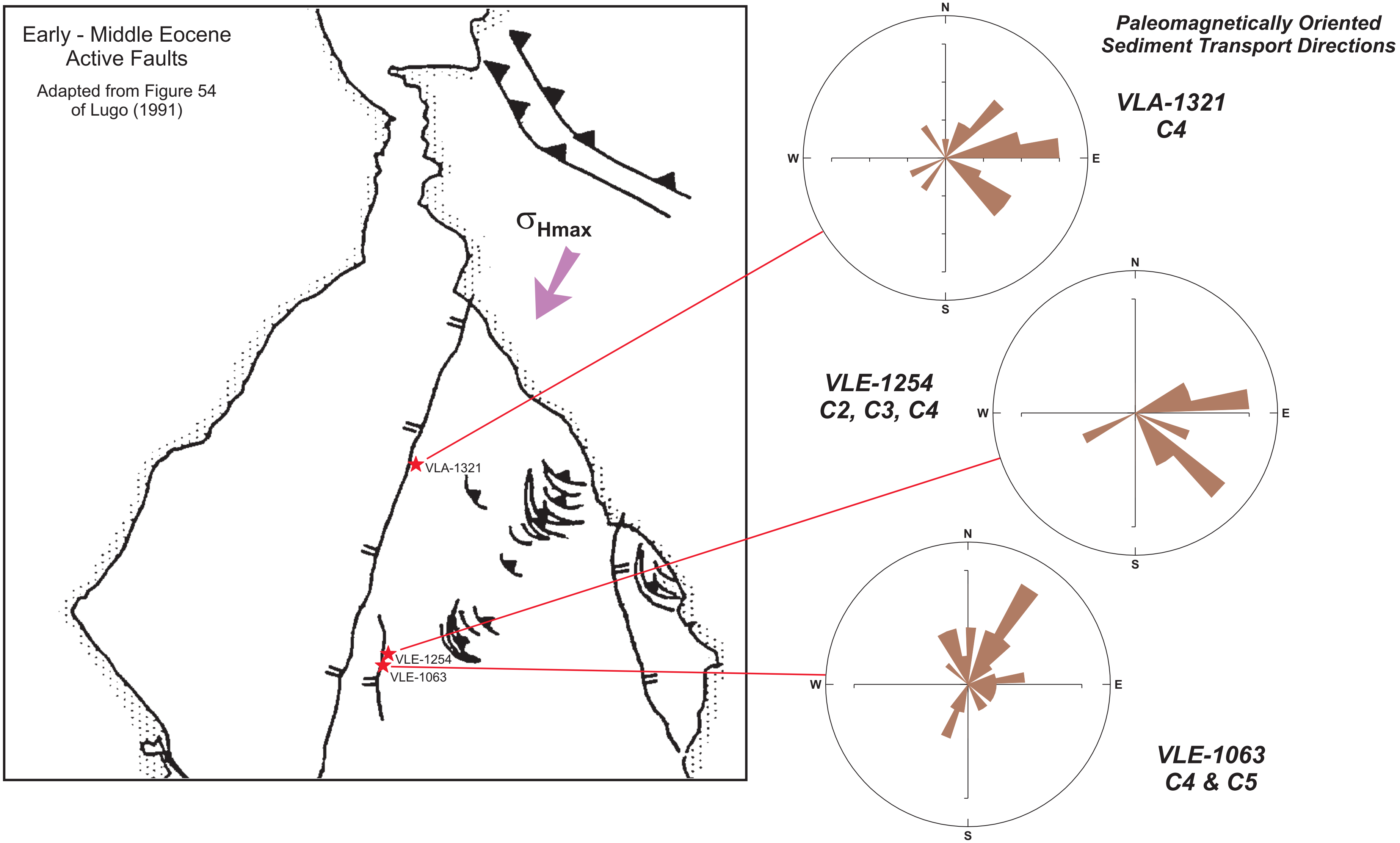


Figure 7. The easterly sediment transport directions in Eocene C cores from VLA-1321, VLE-1254, and VLE-1063 could reflect these wellsites being on the upthrown, east side of the Icotea and VLE faults. These faults were active normal faults in the Early Eocene (~52 Ma), when the paleo σ_{Hmax} direction was probably ~28º. On the east side of these faults, rivers probably flowed eastward, off the structural highs.

Explanation of the Easterly Sediment Transport Directions in Misoa C3/C4/C5 in Central Lake Maracaibo by Rivers Flowing Down the East Side of Folds Forming between the Icotea/Lama and between the Icotea/VLE Faults

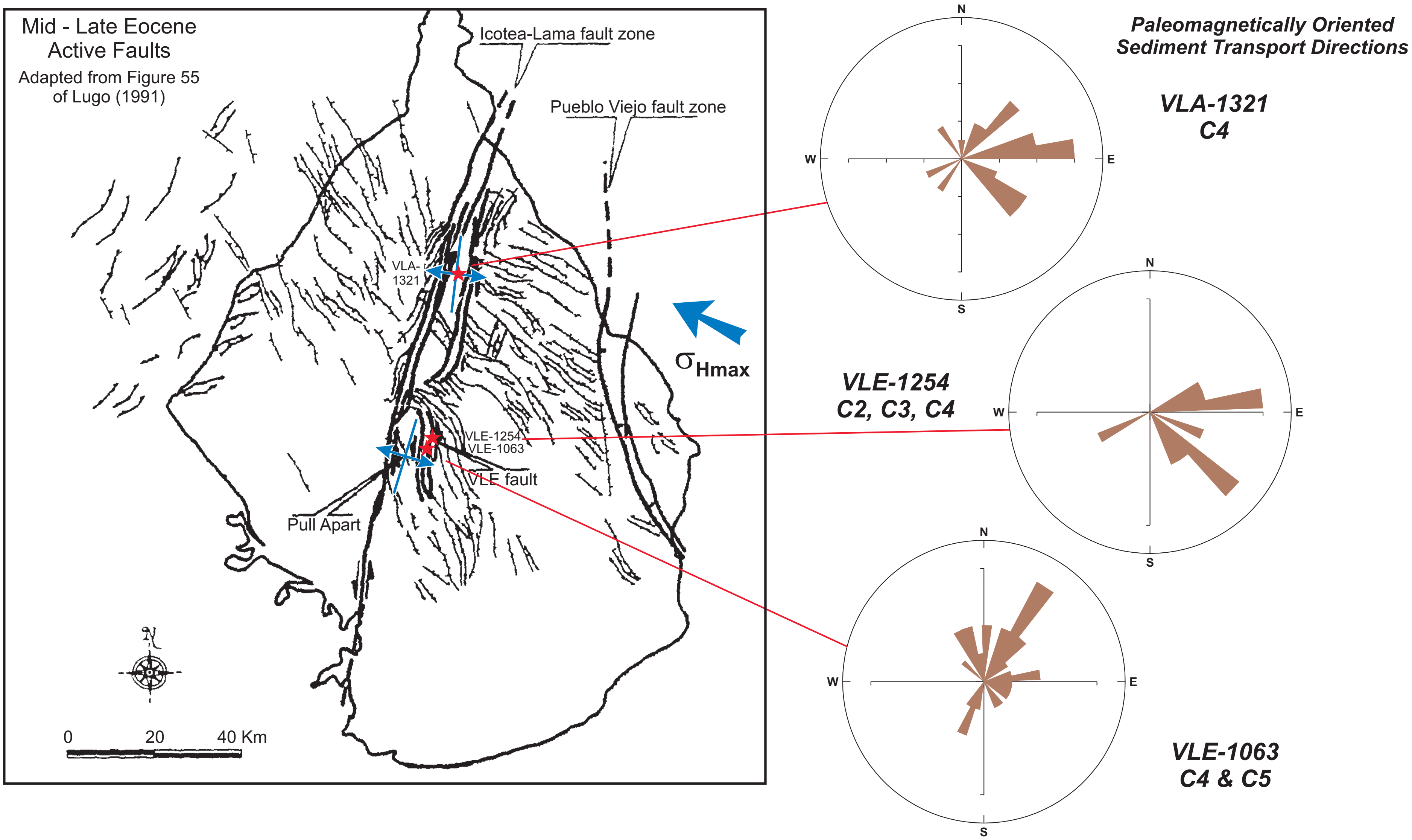
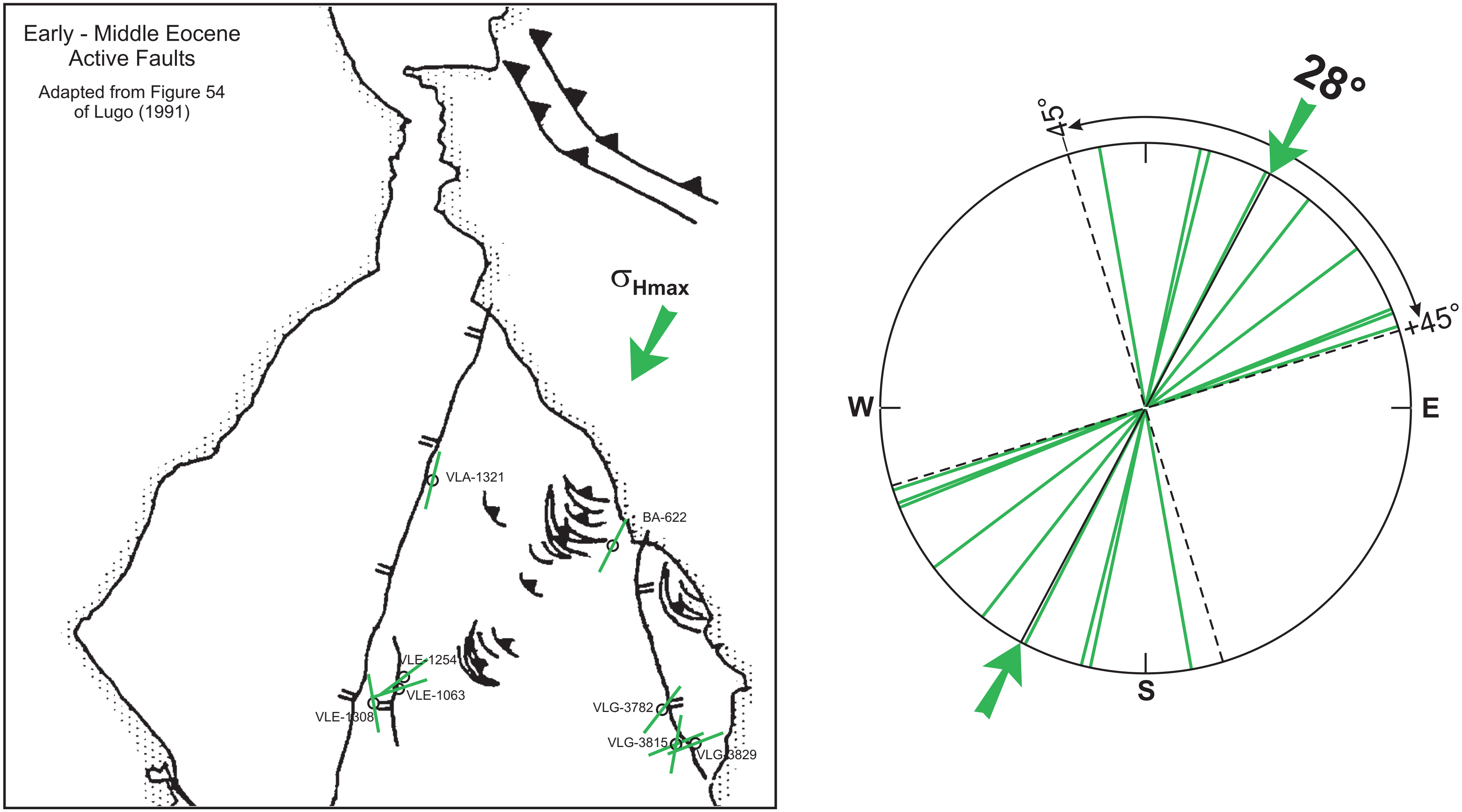


Figure 8. The easterly sediment transport directions in Eocene C cores from VLA-1321, VLE-1254, and VLE-1063 could reflect these wellsites being on the east side of anticlines forming between the Icotea/Lama faults (“Icotea/Lama horst”) and between the Icotea and VLE faults, when the regional paleo σ_{Hmax} direction was ~116º.

Paleomagnetically Oriented Cleats in Misoa Fm. Coal and Shale in Central and Eastern Lake Maracaibo



Early - Middle Eocene Active Faults

Adapted from Figure 54 of Lugo (1991)

Figure 9. Paleomagnetically oriented “face cleats” in Misoa Formation coal and shale can be explained as reflecting a *regional* N 28° E paleo σ_{Hmax} direction in the foreland of the Eocene fold-thrust belt that has been *locally deflected* (by up to ±45°) to be $||$ or $\perp$ to the Icotea, VLE, and Pueblo Viejo faults.

Paleomagnetically Oriented Natural Fractures
Cogollo (Apon), Mara Field
DM-152, 5863 - 6349 ft

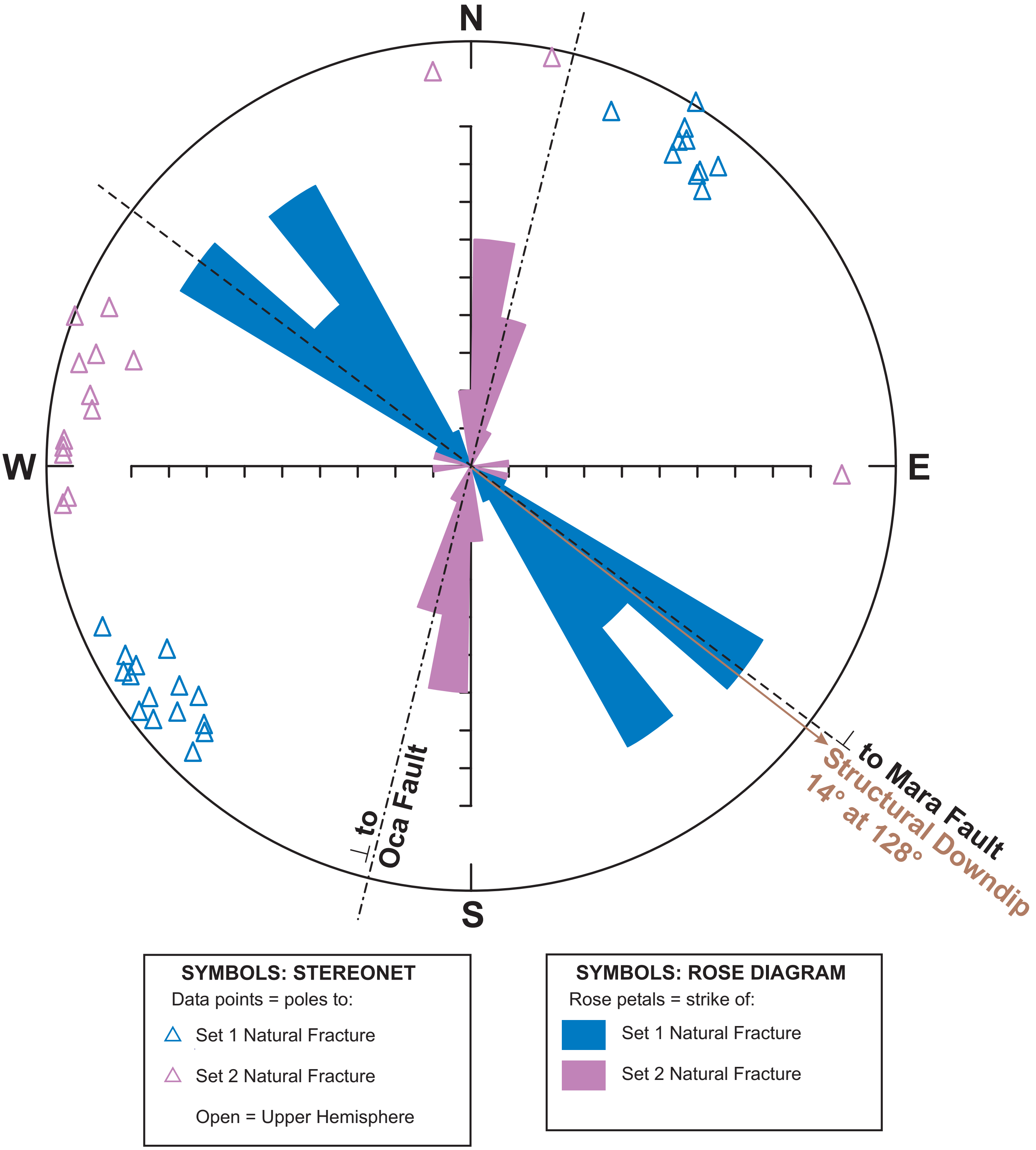


Figure 10. Paleomagnetically oriented poles (stereographic projection) and fracture strikes (rose diagram) of 40 nearly vertical natural fractures in Cogollo (Apon) cores from well DM-152, Mara field. In "geographic coordinates" relative to present-day horizontal. Note that fractures are aligned nearly perpendicular (⊥) to the Mara and Oca faults.

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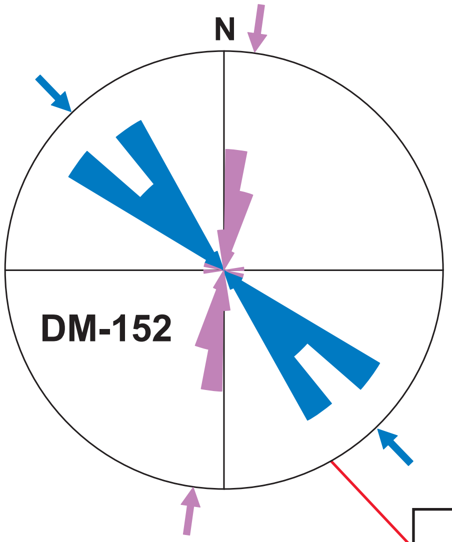
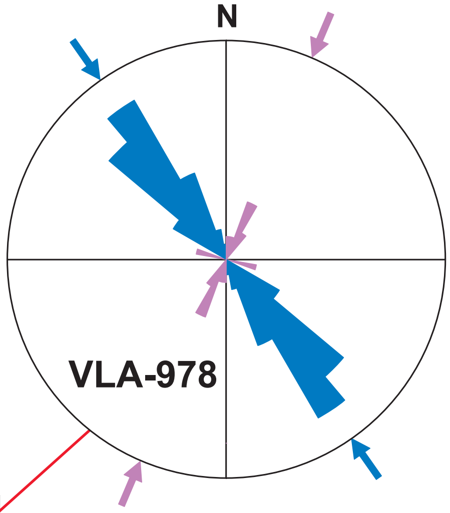
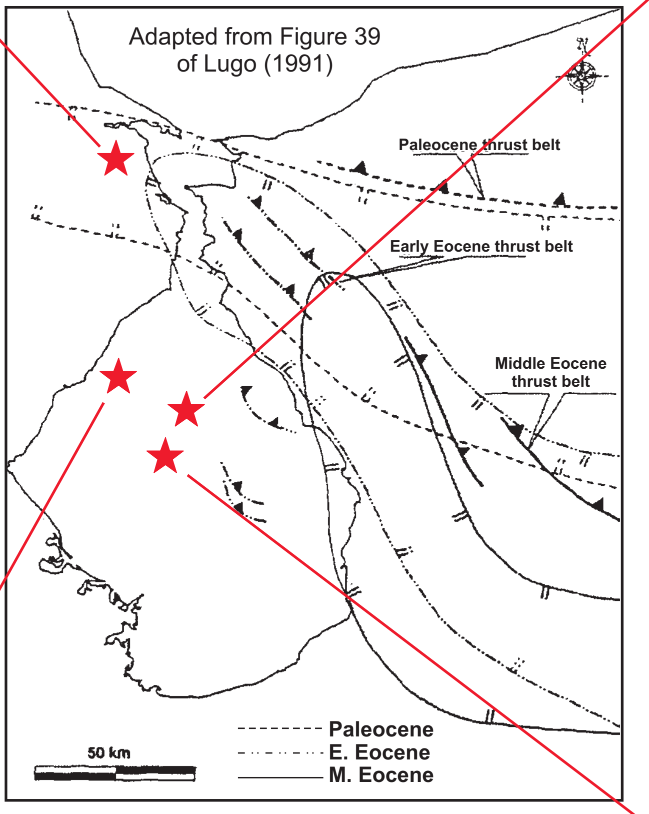
Paleomagnetically Oriented Natural Fractures Cogollo (Apon)







Pattern of migration of the foreland basin from Paleocene to Middle Eocene. Associated thrust belt is also shown.

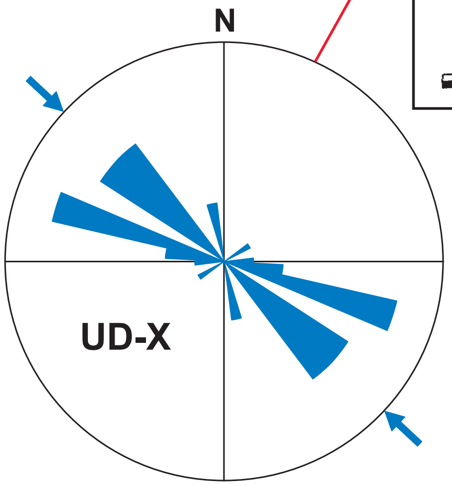
Explanation:

↘ σ_{Hmax} **Set 1**

↓ σ_{Hmax} **Set 2**

Key Points:

- Set 1 fractures are mostly shear fractures striking NW/SE.
- Set 2 fractures form an orthogonal set of extension fractures striking ⊥ and || to Paleogene thrust belt.
- Highest ratio of Set 2 fractures is in DM-152, in Paleogene thrust belt.
- Set 2 fractures die out to the SW.



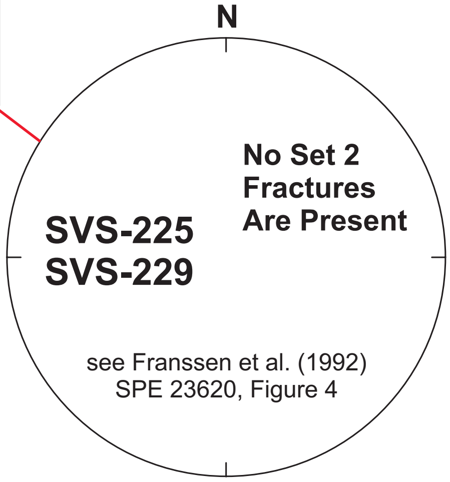
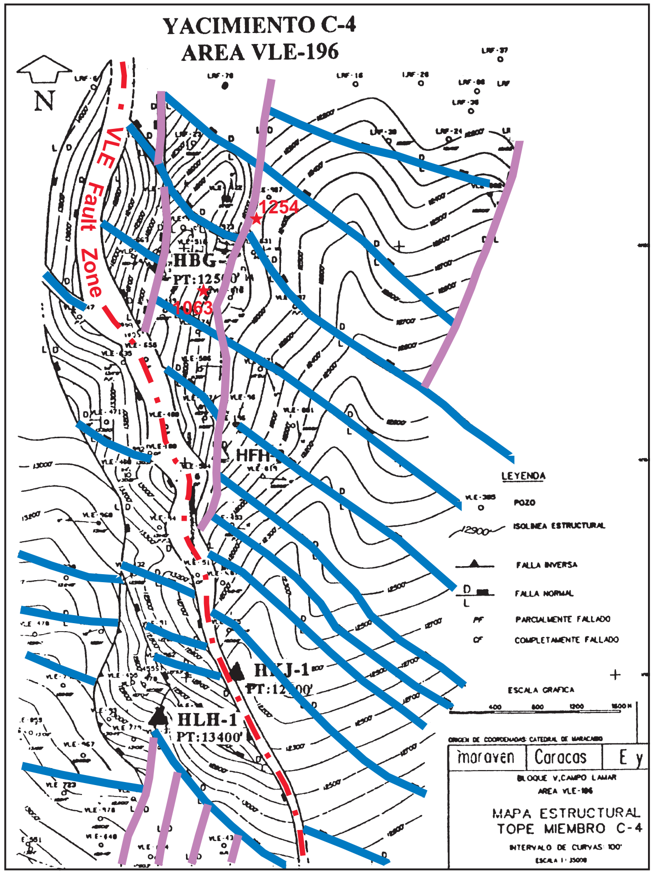
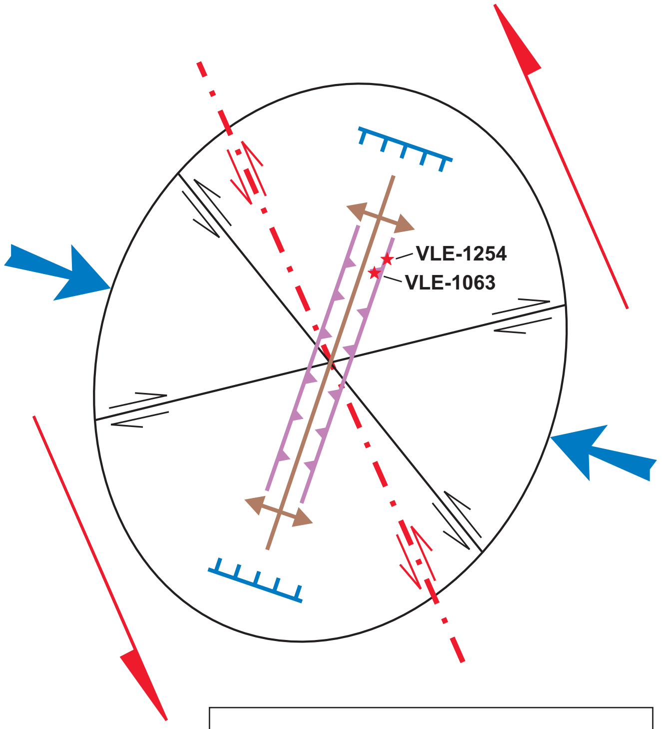
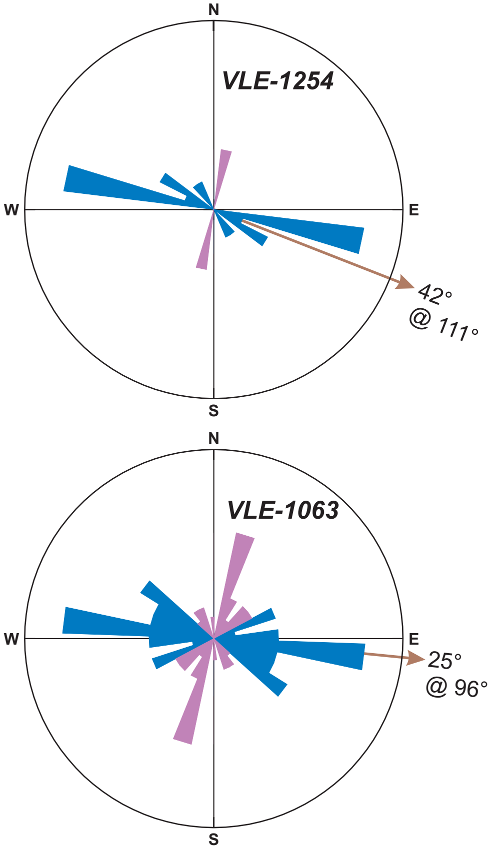


Figure 11. The distribution of NNE/SSW-striking Set 2 fractures relative to the Paleocene/early Eocene thrust belt strongly suggests that Set 2 fracturing occurred during Early Tertiary thrusting. Set 1 fracturing probably occurred in the late Eocene to late Oligocene, when the σ_{Hmax} direction changed to NW/SE, causing compression along NE-trending faults, like Icotea, Urdaneta, and Mara.

Faulting, Fracturing, and Folding as a Consequence of “Restraining Bend” Tectonics





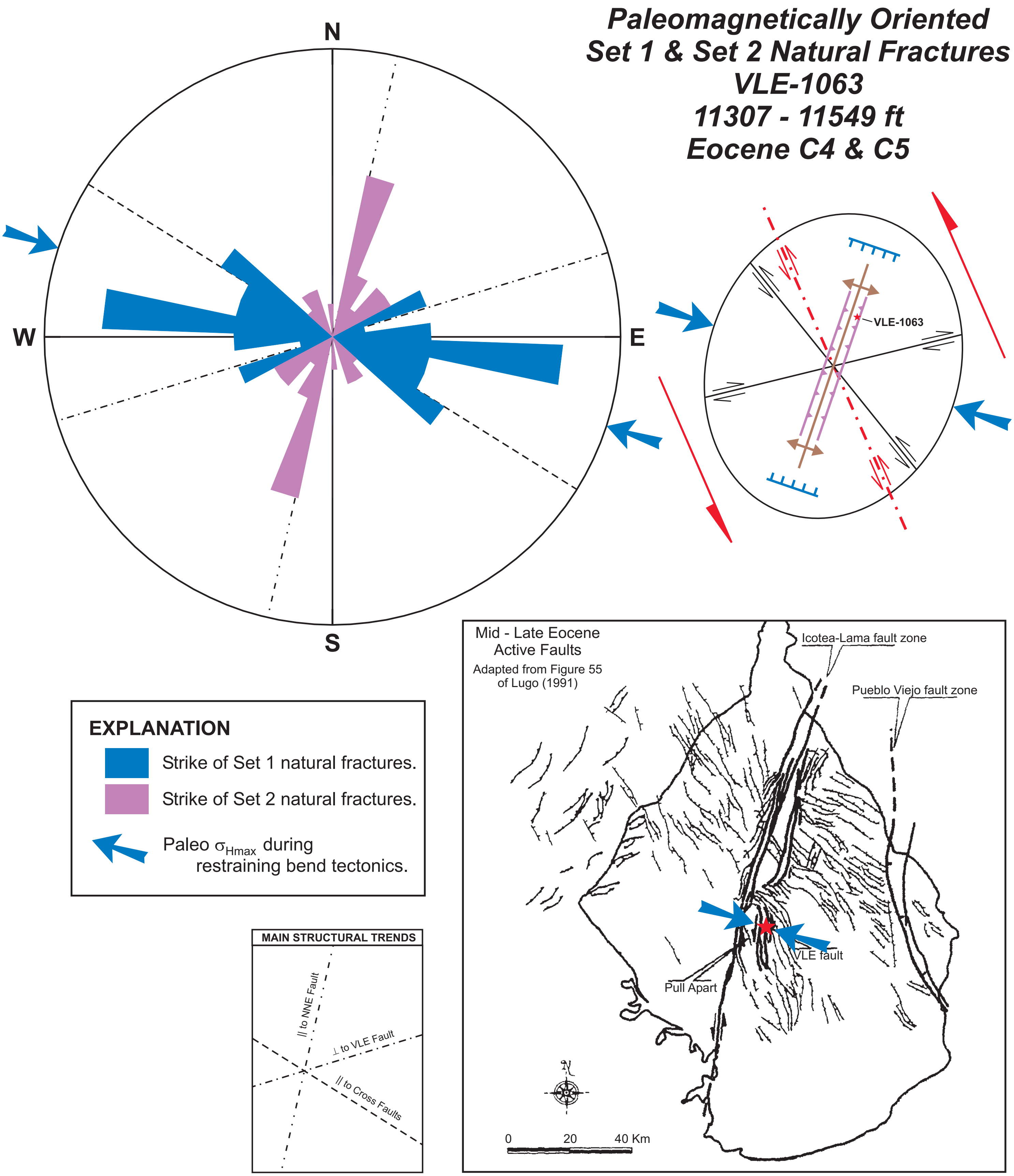


←	Paleo σ_{Hmax} (restraining bend tectonics)
┬┬┬┬	Strike of extensional feature
▲	Strike of compressional feature
↔	Bedding strike and downdip azimuth
⇅	Principal Displacement Zone = VLE fault
✕	Riedel shears

SYMBOLS: ROSE DIAGRAM

🟦	Strike of Set 1 fracture
🟪	Strike of Set 2 fracture
→	Structural downdip from bedding

Figure 12. In paleomagnetically oriented cores from VLE-1254 and VLE-1063, Set 1 and Set 2 natural fractures and structural dip from bedding all probably formed when the paleo σ_{Hmax} direction was WNW/ESE (288°/108°). These angular relationships are consistent with the strain ellipse (simple shear) expected for a “restraining bend” (bend to the right) in a left-lateral strike-slip fault, like the VLE fault. Note that natural fractures in cores are nearly parallel to splay faults and cross faults on map at left.


Paleomagnetically Oriented
Set 1 & Set 2 Natural Fractures
VLE-1063
11307 - 11549 ft
Eocene C4 & C5

EXPLANATION

🟦 Strike of Set 1 natural fractures.

🟪 Strike of Set 2 natural fractures.

← Paleo σ_{Hmax} during restraining bend tectonics.

Figure 13. Paleomagnetically oriented fracture strikes (rose diagram) of Set 1 and Set 2 natural fractures in Eocene cores from well VLE-1063. These natural fractures, which are mostly deformation bands, probably formed during "restraining bend" tectonics, when the paleo σ_{Hmax} direction was WNW/ESE (288°/108°). Note that this direction is nearly parallel to the regional mid-late Eocene extension faults.

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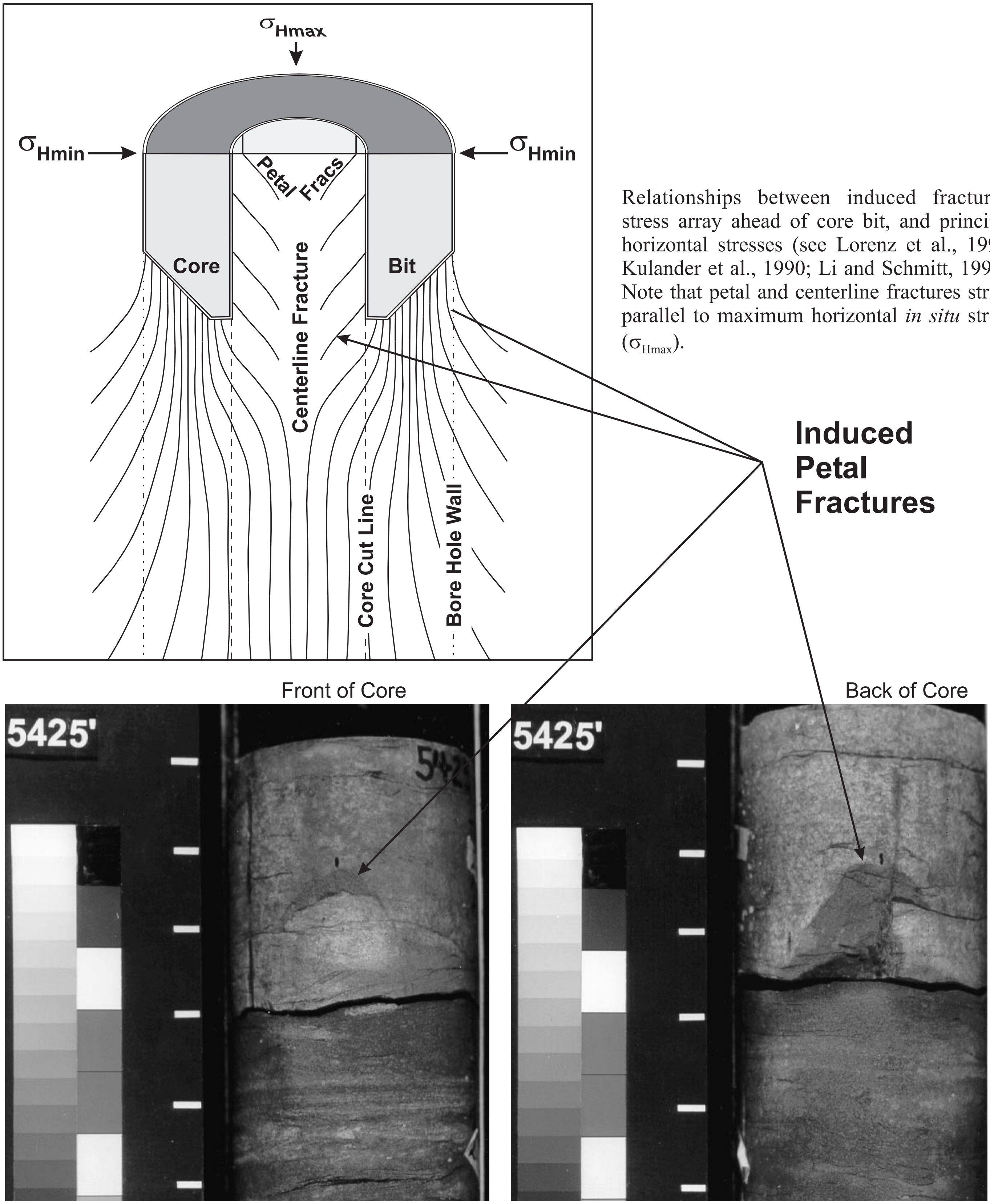
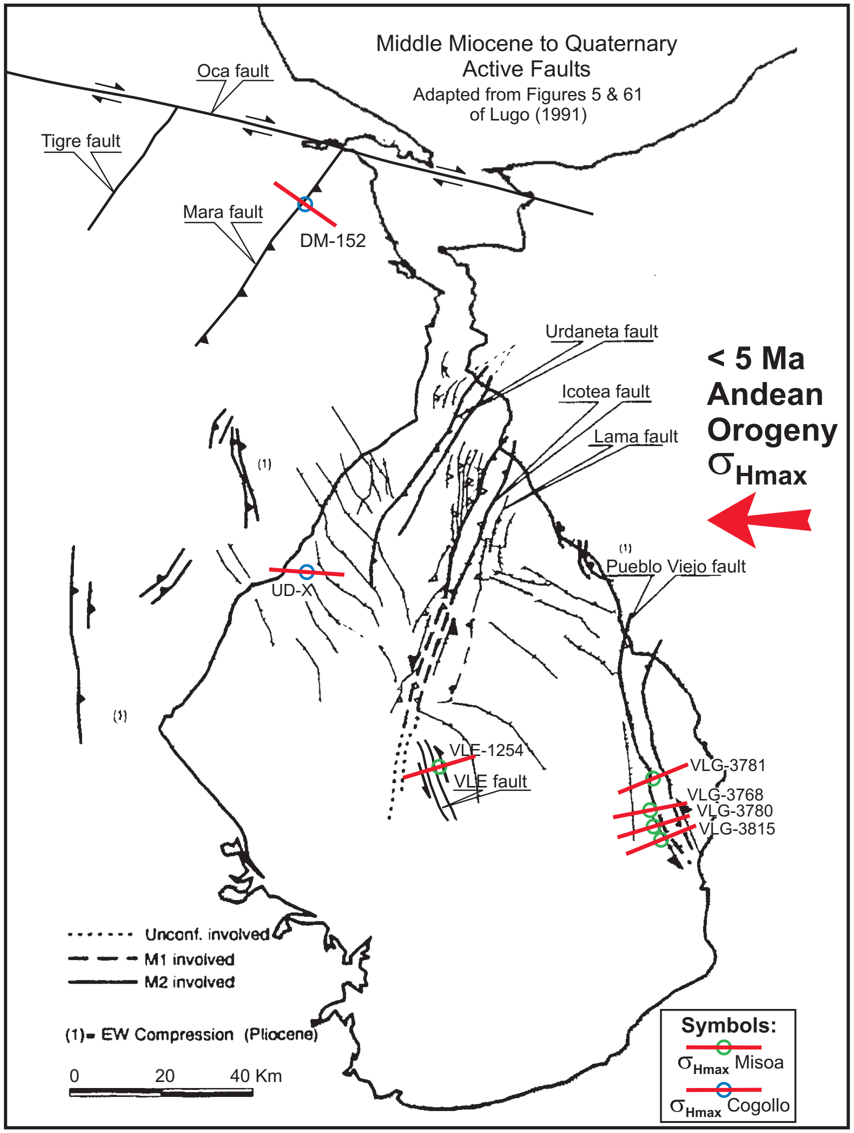


Relationships between induced fractures, stress array ahead of core bit, and principal horizontal stresses (see Lorenz et al., 1990; Kulander et al., 1990; Li and Schmitt, 1997). Note that petal and centerline fractures strike parallel to maximum horizontal *in situ* stress (σ_{Hmax}).

Figure 14. Top = origin of induced petal and centerline fractures relative to maximum horizontal principal stress (σ_{Hmax}). Bottom = typical petal fractures in Eocene core from Lake Maracaibo. Note that petal fractures dip inward toward core center on opposite sides of the core. Note also that petal fractures terminate at sandstone/shale contact.

"Category 1" In Situ Stress Map
Based on Paleomagnetically Oriented Induced Fractures
in Eocene and Cretaceous Cores from the Maracaibo Basin



Category 1 = *In Situ* Stress in
Competent Lithologies (Sandstone & Limestone)
On Flanks of Folds

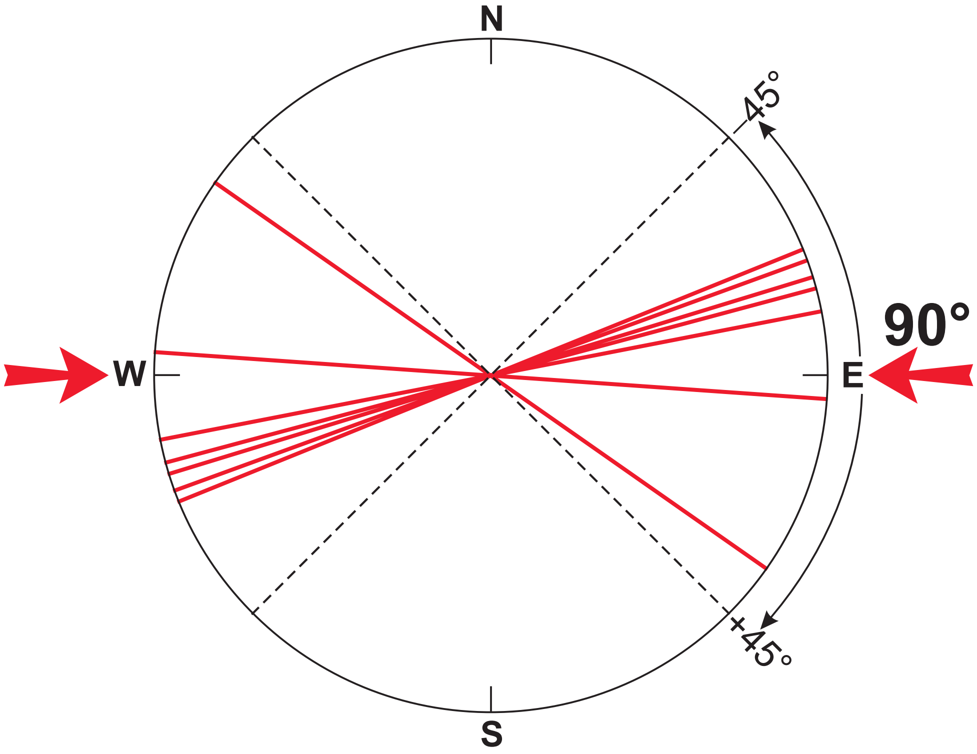
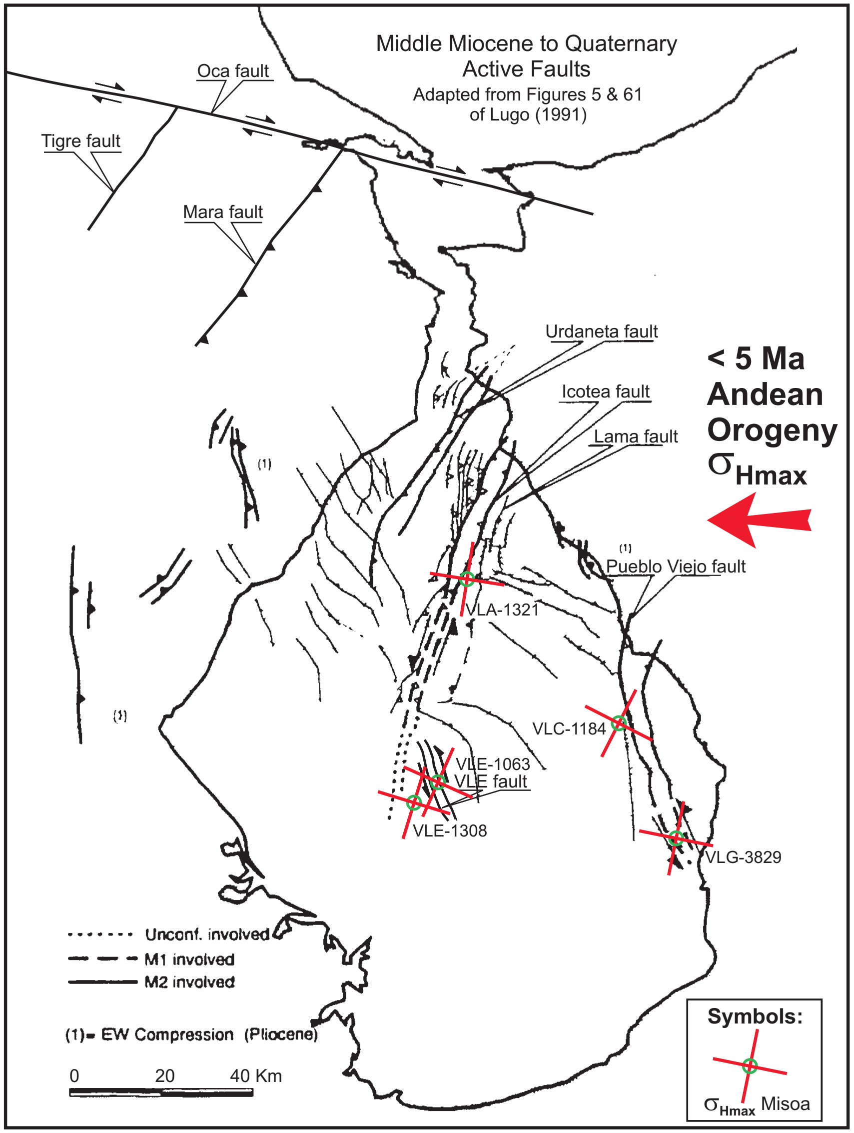


Figure 15. In Eocene (Misoa) and Cretaceous (La Luna/Cogollo) cores from *flanks of folds*, paleomagnetically oriented induced fractures commonly strike ⊥ to nearby faults. This probably reflects a *regional* 90° (E/W) present-day σ_{Hmax} direction (far-field stress from the Andean orogeny) that has been *locally deflected* by up to ±45° to be ⊥ to the Mara, Icotea, VLE, and Pueblo Viejo faults.

“Category 2” In Situ Stress Map Based on Paleomagnetically Oriented Induced Fractures in Eocene Cores from the Maracaibo Basin



Category 2 = *In Situ* Stress in Competent Lithologies (Sandstone & Limestone) Near Crests of Folds

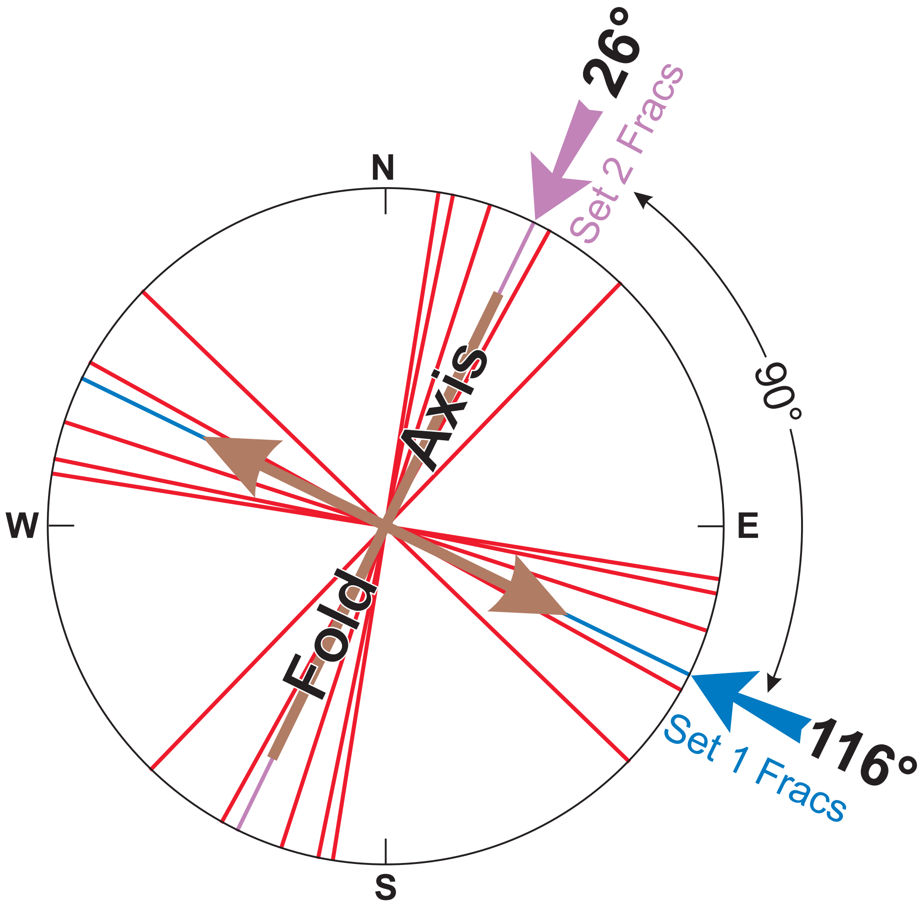


Figure 16. In Eocene (Misoa) cores from near *crests of folds*, paleomagnetically oriented induced fractures commonly form orthogonal sets oriented ⊥ and | | to the NNE-trending fold axes, like Set 1 and Set 2 natural fractures. These folds formed during transpressional events, which occurred both in the Middle to Late Eocene and in the Middle Miocene to Pliocene. Thus, present-day *in situ* stress in crestal wells is controlled by local “bending anisotropy” (Cobbold & Watkinson, 1981) within the folds, rather than by the E/W Andean orogeny far-field stress.

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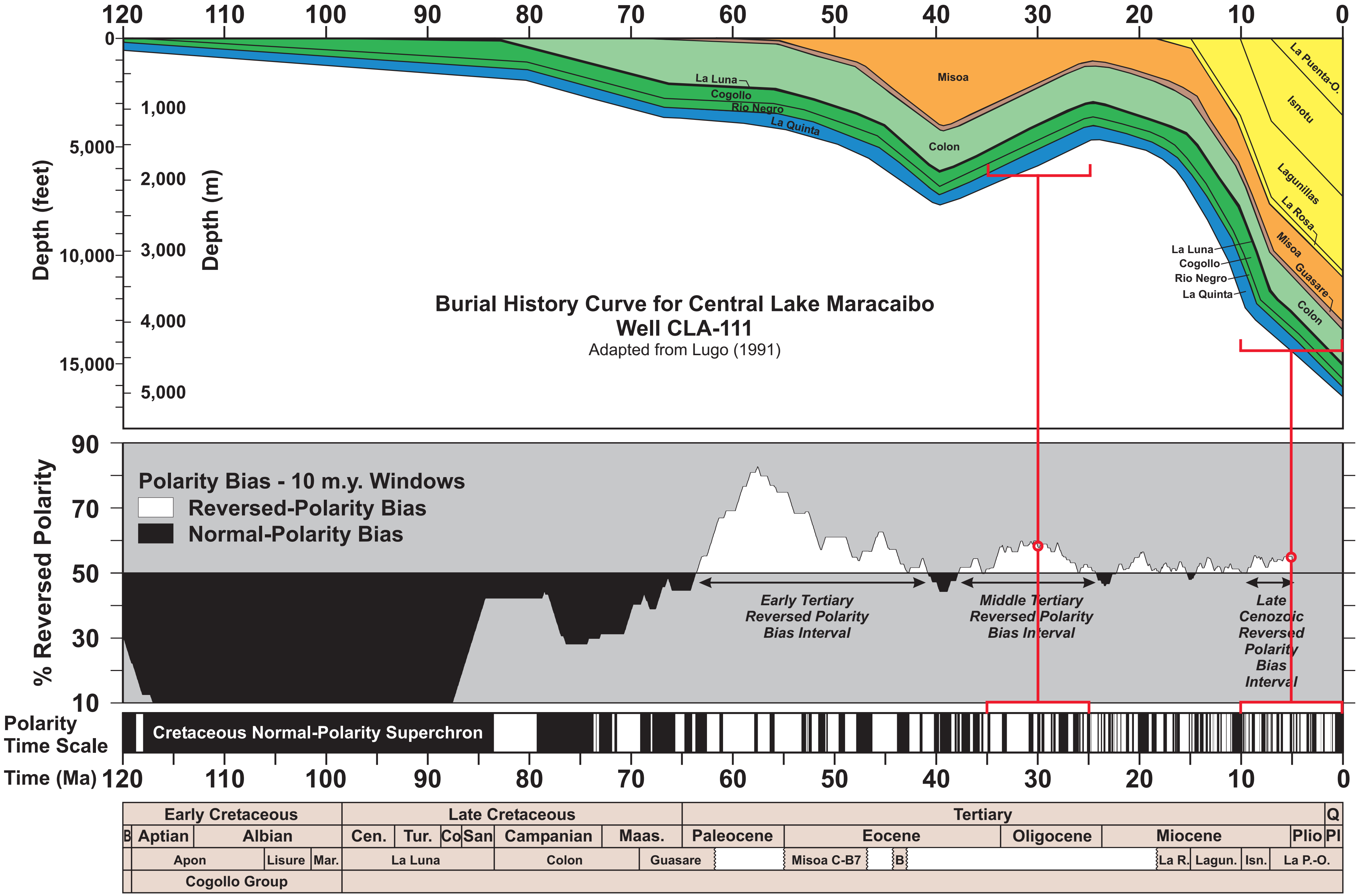

Figure 17. Cretaceous (Cogollo and La Luna) cores from Lake Maracaibo contain a *reversed-polarity* magnetization, despite their depositional ages during the Cretaceous *normal-polarity* superchron. This reversed-polarity magnetization, which also exists in Eocene (Misoa) cores, probably is a "secondary" chemical remanent magnetization (CRM) acquired either during uplift in the Oligocene or during maximum burial (past 10 million years).