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SUBJECT: Addendum to June 1980 response to Question 361.63 re origin of folds & faults,offshore & south of facility.Four composite geologic cross-sections encl.

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ADDENDUM TO RESPONSE 361.63

The June, 1980, response to NRC question 361.63 described the extensive seismic reflection profiling surveys that have been conducted offshore San Onofre during the last ten years. In that response, the purposes of the various surveys and their relevant interpretations about a postulated connection of the Cristianitos fault and the OZD were presented. Evaluation and interpretation of these surveys have led to the conclusion there is no connection between the Cristianitos fault and the OZD. Minor deformational features (e.g., folds and faults) do exist in the submerged bedrock intervening between the seacliff exposure of the Cristianitos fault and the OZD, but these do not represent southward extensions of the Cristianitos. However, explanations of the possible origins of these features were not addressed in the response.

This addendum, therefore, describes briefly the nature of near-surface structural features between the coast and the OZD along the projected trend of the Cristianitos fault, identifies several plausible tectonic and nontectonic origins for the features, and discusses the evidence for their age. The conclusions drawn from this analysis are:

1. There is strong evidence that the features are a result of a gentle deformation involving a combination of tectonic and nontectonic origins.

2. The features do not displace or deform the submerged marine-terrace platform or the overlying terrace deposits, indicating a minimum age of about 13,000 years for the features. Additionally the features do not disrupt the onshore terrace platform dated at older than 125,000 years.

<u>Description of the Nearshore Structural Features</u>

Despite many seismic-reflection profiles in the intervening area between the coast and the OZD, no clear seaward extensions of the Cristianitos fault or of any other continuous structural feature have been found. The most plausible reasons for this are: a) displacement on the Cristianitos fault is rapidly dying-out southward, and b) the expression of the Cristianitos fault might be masked by deep landslide deposits (gravity glide) of late Miocene to early Pliocene age derived from seaward-dipping Monterey Formation in the San Onofre Mountains east of the fault. A number of profiles several thousand feet offshore display continuous reflection-horizons across the projected trend of the Cristianitos fault, indicating the fault could extend seaward no more than about 6,000 feet.

These same profiles do reveal the presence of minor structural features in the shallow bedrock between the coast and the OZD. These features consist mainly of small gentle folds arranged in two belts (Fig. 361.63-4 and Plate 2). One belt lies landward of the OZD and contains folds trending about N45W subparallel to the OZD. The other belt is about two miles wide and extends along a trend of about S25E from a location about two miles southeast of SONGS (west 6000 feet of the inferred offshore extension of the Cristianitos fault) to the OZD, eight miles southeast of SONGS. As this belt of small folds approaches the OZD, it bends eastward and continues along the landward side of the OZD. Folds within this belt have axes subparallel to the trend of the belt. Some of the folds can only be recognized in a single acoustic profile even though profiles are generally closely spaced (less than 1500 feet apart). The longest fold can be traced for about three miles. The spacing between the axes of adjacent folds is generally between 500 and 2000 feet. The folds have very gently inclined limbs with bedding characteristically dipping less than about 10 degrees. The difference in elevation between the crests of anticlines and the troughs of adjacent synclines ranges from a few tens of feet to a maximum of about 300 feet when measured along the projection of a single reflecting horizon (See Plates 1, 3, 4, and 5).

Features suggestive of minor faulting are present in a few places along acoustic profiles in the area landward from the OZD. Most are only visible on a single profile and cannot be located on the adjacent profiles, thus precluding determination of fault orientation and demonstrating the minor nature of the faulting. Although some fault-like features occur along possible projections of the Cristianitos fault, unfaulted reflectors in intervening profiles make correlation highly doubtful and preclude the existence of a throughgoing fault.

Age of the Nearshore Structural Features

The structural features present in acoustic profiles of the nearshore shallow bedrock do not penetrate the erosion surface on top of the bedrock or the overlying terrace deposits. The erosion surface was probably formed following a transgressive sea level about 14,000 years ago. Terrace deposits overlying the erosion surface have yielded carbon-14 ages as old as 13,000 years as disclosed by Vibracore sampling of the offshore sediment. We conclude from this that the structural features are at least as old as 13,000 years and are probably older.

The structural features can be no older than the strata than contain them. Most of the structural features occur offshore from exposures of the Monterey Formation to the southeast of the Cristianitos fault. Fossils obtained from exposures of the Monterey Formation along the beach are of Middle to Early Late Miocene age (12 to 15 million years old). The Monterey Formation has a gentle seaward dip such that the shallow strata offshore would be somewhat younger than those exposed along the beach. To the northwest of the Cristianitos fault, coastal exposures consist of the San Mateo and Capistrano Formations. They are of Late Miocene age (about 5 to 10 million years old) where exposed along the beach. Strata along the beach are nearly horizontal; consequently, bedrock in the nearshore area is probably of Late Miocene age also. Fossils obtained from a shallow bedrock sample taken 10,000 feet directly offshore from SONGS are of latest Miocene age (about 5 to 8 million years old). Beds of Early Pliocene age (about 4 to 5 million years old) are exposed a short distance inland from the coast within the Capistrano Embayment and are probably also present in the offshore area landward from the OZD. Therefore, the structural features are younger than 15 million years. Those that might be related to movement on the Cristianitos fault would have ages in the range of over 125,000 years to 5 million years.

Plausible Origins of Nearshore Structural Features

There are several plausible origins for the shallow structural features observed in acoustic profiles from the area between the coast and the OZD. Those of nontectonic origin include:

1. Primary depositional features associated with submarine channel and fan deposits within the nearsurface bedrock;

2. Differential compaction over an uneven surface on the San Onofre Breccia and around sand bodies;

3. Subaerial landsliding during low stands of sea level, and

4. Deepseated gravity gliding (may occur in combination with tectonic deformation).

Those of tectonic origin include:

1. Drape folding induced by faulting in the underlying San Onofre Breccia;

2. Folding induced by synclinal bending of the underlying San Onofre Breccia;

3. Deformation resulting from deepseated right-slip faulting (wrench fault tectonics), and

4. Deformation resulting from dip-slip displacement on the Cristianitos fault and regional crustal extension (E-W).

The features observed in the acoustic profiles are probably of several origins. As indicated in the discussion below, no single mechanism is likely to account for all of the features.

Primary Depositional Origin: Some features interpreted as gentle folds and minor faults are probably primary sedimentary structures. The Middle Miocene to Early Pliocene formations which form the shallow bedrock between the coast and the OZD contain extensive, complex submarine channel and fan deposits as seen in exposures along the coast from Dana Point to Oceanside. The submarine channel and fan deposits dominantly consist of medium to coarse-grained sandstone and conglomeratic sandstone characterized by large-scale low-angle cross-bedding and lenticular bedding and, near fan heads, by massive bedding. Deposits of interfan and overbank origin consist of siltstone, mudstone, shale and fine-grained sandstone characterized by parallel bedding. Some features which appear to be folds, as seen in the acoustic profiles, are probably the result of nonparallel bedding within the submarine channel and fan deposits. Others may be the result of the draping of interfan deposits over fan lobes with the structure enhanced by differential compaction. Sedimentary structures which might easily be mistaken for faults when seen in acoustic profiles include steeply inclined submarine channel walls where coarse-grained indistinctly-bedded sandstone has been backfilled against fine-grained thinly-bedded sediments, and landslides, slumps and case of the asymmetrically-arranged, nested, submarine-channel deposits exposed at San Clemente State Beach (described by Walker, 1975), an acoustic profile of them would probably resemble a series of backward-rotated fault blocks.

For more detailed information on the submarine channel and fan deposits exposed near Dana Point, refer to Bartow (1966, 1971), Normark and Piper (1969), Piper and Normark (1971), and Normark (1979). For those exposed near San Clemente State Beach, refer to Weser (1971), Walker (1975), and Hess (1979). For those of the San Mateo Formation near SONGS and the Monterey Formation southeast of the Cristianitos fault and for the paleogeographic and paleotectonic settings of these deposits, refer to Ehlig (1977, 1979a, 1979b) and to the discussion below on the Cristianitos fault.

Sedimentary features are most likely to account for folds and faults which cannot be correlated from one acoustic profile to the next. They can readily account for the lack of continuous reflectors in some areas and for small-scale, apparent structural complexities.

Differential Compaction: Differential compaction is a common cause of low amplitude folds and minor faults. The differential compaction may result from the prograding of loosely compacted sediment across a topographic surface developed on highly compacted rocks. As the sediment undergoes compaction, it acquires a structure similar to that of the underlying surface. The relief on a compactional structure tends to diminish in an upward direction. In the case of the SONGS area, the shallow nearshore bedrock rests unconformably on the San Onofre Breccia. In exposures along the coast immediately southeast of SONGS there is as much as 100 feet of local relief on the unconformity produced by the erosion of wavecut benches and cliffs as the Middle Miocene shoreline transgressed toward the east-northeast. It is not clear how much relief is present along the unconformity in the offshore area. Thus, it is difficult to assess the likelihood of the offshore folds being formed by this mechanism. The trends of offshore folds are compatible with what is known about the trends of Miocene shorelines.

Compactional structures may also develop where compactible sediments, such as silt, clay and biogenic oozes, are deposited adjacent to relatively incompactible sediment, such as sand and gravel. Compactional structures of this origin are undoubtedly present within the submarine channel and fan deposits in the shallow offshore bedrock, but would blend with structures of primary depositional origin and be nearly indistinguishable in acoustic profiles. However, if fossil beach ridges exist on the unconformity above the San Onofre Breccia, differential compaction over the top of them might produce folds similar to the folds in the offshore area. It is unknown whether such beach deposits occur in the offshore area.

Thus, differential compaction might be a factor in the development of the shallow nearshore structure; however, insufficient data are available to evaluate its importance.

<u>Subaerial Landsliding</u>: Extensive landslides occur along the present sea cliffs southeast of the Cristianitos fault. The landslides occur wherever wave erosion has undercut clay-rich beds in the seaward dipping Monterey Formation. As such, individual slides can extend for great distances along the coastline. For example, almost continuous landslides extend southestward from the Cristianitos fault for a distance of 2-1/2 miles. The only areas where the sea cliffs have not failed are those underlain by coarse-grained sandstone of submarine fan origin. The individual slides extend inland to the

point where the slip surface in the Monterey Formation is truncated by the unconformity at the base of the overlying Pleistocene terrace deposits. This distance ranges between 200 and 600 feet measured perpendicular to the coast. Slide movement characteristically involves backward rotation and formation of a graben or trough along the head of the slide, and an upthrust, translational glide or anticlinal upwarp along the toe of the slide.

About 17,000-20,000 years ago during the Wisconsin glacial stage, sea level is believed to have been about 425 feet lower than it is today. At that time most of the area between the present coast and the OZD should have been above sea level. Extensive landslides probably occurred along the sea cliffs at that time and may have toed out below sea level because of the relatively steep offshore slope in that area. Such sliding might account for some of the deformation observed in profiles across the OZD.

As sea level rose following a low stand 17,000-20,000 years ago, wave erosion should have cut away the tops of landslides leaving only the deeper parts of slide masses intact. Continued sliding probably occurred along each successive shore line; however, most slide masses were probably removed by wave erosion except at times when sea level rose rapidly. Remnants of slide masses are most likely to be preserved along the landward side of submerged terrace deposits. Any slide masses which remain should be characterized by long axes parallel to old shorelines and by basal slip surfaces which project out of the bedrock near old shoreline angles. The slide remnants might appear as closely spaced anticline-syncline pairs with the syncline located on the landward side. Structures of landslide origin are likely to extend less than

100 feet into the bedrock except along the break in slope near the OZD where they might be deeper. Most of the folds visible in acoustic profiles appear to be larger than would be expected if they were of subaerial landslide origin.

Gravity Gliding: As used here, gravity gliding refers to downslope slippage of a rock mass on a larger scale than an ordinary landslide. In order to occur, the rock mass must be on a slope with a basal slip surface (commonly a bed of weak material) inclined in the direction of slope. The upslope end of the glide mass must either be unattached (truncated by erosion) or pulled apart from its headward extension. The toe of a gravity glide commonly occurs where the dip of the basal slip surface flattens to nearly horizontal or reverses its direction of inclination, or where the ground surface becomes nearly horizontal, as along the floor of basin. In such cases, lateral shortening in the toe area is accommodated by folding or thrusting that results in uplift of the ground surface. Shortening may also be accommodated by lateral compaction of materials within the toe area or by tectonically-controlled extension adjacent to the toe.

During the Pliocene, conditions appear to have been highly favorable for the creation of folds within the Monterey Formation southeast of SONGS by gravity gliding. The Monterey Formation which forms the nearsurface bedrock in coastal exposures southeast of the Cristianitos fault was originally deposited across the top of the San Onofre Mountains (Ehlig, 1977 and Plates 1, 3, 4, 5). Remnants of the basal part of the Monterey Formation are still present along the northwestern crest of the mountains. Since its deposition, the Monterey Formation has been tilted seaward (west-southwestward) at an average angle of about 20 degrees along the west flank of the San Onofre Mountains (refer to maps and cross sections accompanying report by Ehlig, 1977 and Plates 1, 3, 4, 5). The tilting probably occurred gradually during the Late Miocene and Pliocene. Tilting was complete or nearly complete by the end of the Pliocene as shown by the absence of noticeable tilting of marine terraces on the west flank of the San Onofre Mountains. The oldest terraces appear to be late Pliocene in age (Ehlig, 1980). As the Monterey Formation underwent seaward tilting along the flank of the San Onofre Mountains, it was probably not buttressed by the accumulation of sediments on its seaward side. A study of the evolution of the Capistrano Embayment (Ehlig, 1979a, 1979b) demonstrates that a westward-facing submarine scarp existed along the Cristianitos fault at the northwest end of the San Onofre Mountains during the Late Miocene and Early Pliocene, and that a submarine fan along the base of the scarp was feeding sediment into a deep marine basin to the south and west. In view of this, it is highly unlikely that a shallowly-floored basin occurred along the seaward side of the San Onofre Mountains during this time. Instead, a steep submarine slope probably existed along the top of the Monterey Formation in this area. Such a slope would be favorable for gravity gliding of the Monterey Formation off of the steep flank of the San Onofre Mountains. The gliding would be accommodated by shortening through folding in the present nearshore areas where the regional dip of the Monterey Formation is very gentle.

If the nearshore folds are of gravity glide origin, they should terminate at depth along one or more slip surfaces and should not continue downward into the underlying San Onofre Breccia. The shortening shown by the folds would be equal to the amount of displacement within the upper part of the glide and is not likely to exceed several thousand feet. Such gliding would most likely have occurred during the Late Miocene or Early Pliocene. Low dips in the San Mateo Formation and very low-gradient slopes in the offshore area west of the Cristianitos fault preclude modern gravity gliding in the vicinity of SONGS. Minor faulting in the offshore area could also be accounted for by gravity gliding.

Drape Folding: Drape folding consists of passive deformation within sediments draped across a base which is experiencing local upward or downward movement. In this case, the base would be the top of the San Onofre Breccia and the deformation would most likely result from dip-slip faulting. (Small scale folding is unlikely to occur in the San Onofre Breccia because it is a thick, rigid unit with few bedding planes suited for flexural-slip surfaces.) Drape folds would have the same alignment and general shape as the underlying structure. Where developed over dip-slip faults, drape folds would tend to be chevron-shaped near the base but would tend to broaden and take on a gentler form in an upward direction, providing the sediments were relatively plastic. Faults might also be expected to propagate upward into the sedimentary cover, though they are typically replaced by bending. When deformation occurs simultaneously with sedimentation, drape folds die out upward in a manner similar to folds formed by differential compaction resulting from sedimentation across an uneven surface.

The structures in the shallow bedrock might be of drape origin, but available data do not favor such an origin over other possible origins. If they are of this origin, they have probably developed across a wide zone of small north-northwest-trending dip-separation faults within the underlying San Onofre

Breccia. The faults would typically be downthrown on the landward side as indicated by the tendency for the folds in the shallow bedrock to have steeper and shorter landward-facing limbs than seaward-facing limbs. Such faults might be similar to those cutting the Monterey Formation on the west flank of the San Onofre Mountains and might be the result of brittle deformation within the San Onofre Breccia as it was bent downward along the coast. Such deformation is not likely to represent an offshore continuation of the Cristianitos fault. The Cristianitos fault is down on the west and has its displacement concentrated in a narrow zone.

Folding Induced by Synclinal Bending of the San Onofre Breccia: During bending, the San Onofre Breccia should behave as a competent member. Less competent material resting on the breccia, such as the Monterey Formation, should experience compression in areas where the breccia is undergoing synclinal downwarping. This could produce small folds in the less competent overlying material with axes parallel to the axis of the downwarp. The Monterey Formation has a broadly synclinal structure between the San Onofre Mountains and the area immediately offshore. This may reflect the presence of a synclinal downwarp in the underlying San Onofre Breccia. Sparse data by Western Geophysical (1972) on the acoustic travel time to effective acoustic basement (probably San Onofre Breccia) also seems to favor the existence of a relatively flat structure in the nearshore area. It is possible that such warping of the San Onofre Breccia, perhaps in combination with minor faulting within the breccia because of its brittle nature, is responsible for many of the structural features present in the shallow nearshore bedrock.

<u>Folding Induced by Strike-Slip Faulting</u>: Because the OZD is commonly considered to be a zone of right slip, it would be reasonable to suspect that the shallow nearshore structures might have been formed by wrench tectonics. The term "wrench tectonics" is generally applied to near surface deformation above a deepseated fault or fault zone which has experienced strike-slip displacement. In places where a fault or fault zone is overlain by a sedimentary cover, strike-slip displacement typically produces <u>en echelon</u> sets of folds and faults in the sedimentary cover overlying the fault (Fig. 361.63-3). The folds tend to be domal anticlines with their long axes forming an acute angle to the left of the fault in the case of right slip and to the right of the fault in the case of left slip. Reverse faults may also develop in the orientation of the folds. A set of <u>en echelon</u> normal faults tends to develop with their strikes forming an acute angle to the right of the master fault in the case of right slip and to the left in the case of left slip.

Such features are well developed along the Newport-Inglewood zone of deformation as described by Harding (1973). However, they are absent or are incorrectly oriented within the offshore area between the coast and the OZD near SONGS. In the case of the folds in the shallow nearshore bedrock, the folds have a parallel arrangement rather than being <u>en echelon</u> and have the opposite orientation from that which would result from right shear along the OZD (Fig. 361.63.4). No conclusions can be reached regarding the geometric significance of the minor faults in the nearshore area because their orientation and sense of displacement are unknown. Folds along the OZD tend to parallel the zone and, therefore, provide no information on the nature of faulting along the zone. The Cristianitos fault is a west-facing northward-trending normal fault with an orientation compatible with right slip on the

OZD (and with east-west crustal extension); however, its displacement is greatest near the center of the Capistrano Embayment (about 10 miles from the closest point on the OZD) and decreases both to the north and south from the center (toward the OZD). The recent onshore borings support this. There is strong evidence that the Cristianitos fault lacks a structural or mechanical relationship to the OZD.

Thus, wrench-fault tectonics do not provide a likely explanation for the nearshore structural features.

<u>Dip-Slip Displacement on the Cristianitos Fault</u>: Onshore the Cristianitos fault is a narrow well-defined zone of rupture unassociated with broad folds. Faults of the zone consistently dip steeply west, and displacements are down to the west.

In contrast, the deformational belts offshore are very wide and comprise chiefly broad folds. The short faults do not constitute a discrete or narrow zone, and displacements are commonly undiscernible in the seismic-reflection profiles. The folds are not assymetrically downwarped to the west as they would be if they reflect down-to-the-west displacement characteristic of the Cristianitos fault. In general, folds are not commonly formed in extensional environments.

These observations demonstrate the lack of generic association between the nearshore structural features and the Cristianitos fault.

Conclusions

The nearshore structural features between the coast and the OZD are conceivably of several origins, but they do not represent seaward extensions of the Cristianitos fault, nor are they necessarily of a tectonic orign.

Rather, it is a strong possibility that these features were caused by gently deforming massive, Miocene age fan deposits which had been modified by differential compaction, and possibly subaerial landsliding.

Regardless of the origin of these near-shore features, it is clear that they are older than about 13,000 years since they do not affect the submerged terrace platforms or the overlying deposits, and are younger than about 15 million years. The age of this very gentle deformation which is truncated by the marine terrace platform, is additionally supported by the even older onshore terrace platform, which is not deformed by any features, dated at older than 125,000. Moreover, should these features represent the effects of gravity tectonics, they would be, of necessity, on the order of 3 to 5 million years of age (Late Miocene to Early Pliocene).

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