Comments on the Faulting and Seismic Hazard at San Onofre, San Diego County, California
Submitted by Mark R. Legg, PhD, California Reg. Geologist #6463, Reg. Geophysicist #948.
President, Legg Geophysical, Huntington Beach, California

1. It is now well established that the Rose Canyon and Newport-Inglewood fault zones are continuous, via the South Coast Offshore Zone of Deformation. Consequently, the combined fault system is capable of large earthquakes (M>7). [Fischer and Mills, 1991]

2. It is now recognized that major detachment fault systems in the region are reactivated as thrust faults, some blind (not reaching the surface). The major Oceanside detachment/thrust system underlies the San Onofre Nuclear Generating Station (SONGS). Consequently, large thrust or oblique-reverse earthquakes on this system may generate shaking levels in excess of the design level of SONGS units 2 and 3. [Bohannon and others, 1990; Legg and others, 1992; Nicholson and others, 1993; Crouch and Suppe, 1993; Bohannon and Geist, 1998; Mueller and others, 1998; Grant and others, 1999; Rivero and others, 2000]

   a. The SONGS site would not be 5-7 km from the epicentral zone, but instead directly above the potential fault rupture plane. Estimation of strong motion should use an epicentral distance of zero (0).

   b. Newer attenuation relations based upon recent large earthquake activity including the 1989 Loma Prieta, California; 1992 Landers, California; 1999 Chi-Chi, Taiwan; 1999 Izmit, Turkey; and 1995 Kobe, Japan, and moderate earthquakes including the 1994 Northridge, California; 1987 Whittier Narrows, California; 1983 Coalinga, California; and 1984 Morgan Hill, California are more accurate in estimating ground motions than the relationships used for the Safety Evaluation conducted in the late 1970s. [Abrahamson and Silva, 1997; Boore and others, 1997; Campbell, 1997; Sadigh and others, 1997]

   c. The recent earthquake experience has shown that near source effects are substantial, resulting in strong amplification of ground motions. The SONGS site lies directly above the detachment/thrust system, and therefore is subject to such effects. These effects include focusing of energy due to the rupture propagation and hanging wall effects wherein the seismic energy is trapped and amplified in the wedge of crust above the fault plane.

   d. As stated during my testimony during the NRC hearings in 1981, the reverse fault character of microearthquakes recorded along the Cristianitos fault trend in the mid-1970s and reactivation of minor faulting uncovered during site excavations is consistent with overall reactivation of ancient normal fault structures by a new stress regime involving northeast-directed shortening or transpression. This assertion has now been confirmed by recent geologic studies in the neighboring offshore region, and in fact, may have been deduced from the proprietary exploration industry data available to the Safety Evaluators in the late 1970s.

3. Geologic investigations along the coast in the Carlsbad and Camp Pendleton areas to the south of the SONGS site have identified numerous paleoseismic features indicative of prehistoric large earthquakes along the north San Diego County coastline. [Kuhn and others, 1996; Franklin and Kuhn, 2000; Kuhn and others, 2000]

   a. Abundant evidence of paleoliquefaction has been identified at numerous sites in the Carlsbad and Camp Pendleton area. This liquefaction involved Pleistocene terrace deposits, and in some

EXHIBIT 2 (1 OF 5)

cases, older Eocene siltstone bedrock. It is rare that such older and densified, but not lithified, materials liquefy. Consequently, the recognition of such liquefaction in Holocene time, as evident by involvement of Native American midden deposits, implies that the strong motion (shaking) was very severe. Reasons to expect such severe shaking were outlined above.

b. Some of the ground deformation features identified with the paleoliquefaction include sand blow deposits and craters, low-angle slip surfaces associated with lateral spreading, and numerous shallow sand filled fissures, sand injection dikes, and polygonal structures. Some of these features look remarkably similar to features uncovered during the excavation of the building pads for SONGS units 2 and 3; the nature of these features was unrecognized or unknown at the time of the Safety Evaluations.

4. Large active landslides along the coast immediately south of the SONGS site, at San Onofre State Beach, may have been considered ancient for the Safety Evaluation during the 1970s. The reactivation, and continued movement for more than two (2) years demonstrates that the coastal bluffs are highly unstable along the north San Diego County coastline. Although the surficial lithology and structure are somewhat different at San Onofre, being in the hanging wall of the Cristianitos fault, the relative straight or smoothly curving character of the shoreline and coastal bluff suggests that some active coastal erosion mechanisms, possibly landsliding or block falls, have acted in the past in the San Onofre area to keep pace with the active landslide headward erosion of the coast to the south. This process needs to be investigated to determine what threat exists to the San Onofre site, and whether seawall installed provide adequate protection for such processes. [Ehlig, 1977; Kuhn, 2000]

5. Locally generated tsunami, from large nearby offshore earthquake or submarine landslide, is now recognized as a serious threat to coastal southern California. With the recognition of major oblique components to offshore faulting, including blind thrusts, restraining bend uplifts and transtensional sags along strike-slip faults, major seafloor displacement during large (Mag>6.5) submarine earthquakes are likely to generate tsunami that attack the southern California coast with destructive force. Indeed, long term uplift of coastal marine terraces may attest to infrequent, but large tectonic displacements of the southern California coast. Furthermore, the steep slopes in unstable geologic materials on offshore ridges, banks, and basins, may generate large amplitude tsunami that can be locally destructive to the nearby coast, as occurred in Papua New Guinea. It is likely that large underwater landslides would be triggered by severe earthquakes, and the possibility of both tectonic displacement and landslide inducement of tsunamis exists. Maximum expected run-up maps for locally generated tsunami are currently being prepared for coastal San Diego County. The presence of steep coastal bluffs, like those near SONGS, also tend to amplify the wave so that narrow coastal valleys or lowlands may expect even higher wave run-up than broader low-lying coastal areas. [Field and Edwards, 1993; Lander and others, 1993; McCarthy and others, 1993; Kuhn and others, 1994, 1995; Legg, 1994; Watts and Raichlen, 1994; Bohannon and Gardner, 2001; Legg and Kamerling, 2001; Locat and others, 2001; Tappin and others, 2001]

Abrahamson, N.A., and Silva, W.J., 1997, Empirical response spectral attenuation relations for shallow crustal earthquakes: Seismological Research Letters, v. 68, p. 94-127.

Bohannon, R., Eittreim, S., Childs, J., Geist, E., Legg, M., Lee, C., Sorlien, C., and Busch, L., 1990, A seismic-reflection study of the California Continental Borderland, [abstract] *in* Trans. American Geophysical Union, v. 71, p. 1631.

Bohannon, R. and Geist, E., 1998, Upper crustal structure and Neogene tectonic development of the California continental borderland: Geological Society of America Bulletin, v. 110, p. 779-800.

EX. 2 (2 of 5)

Bohannon, R.G., and Gardner, 2001, Submarine landslides of San Pedro Sea Valley, southwest Los Angeles basin: in Watts, P., Synolakis, C.E., and Bardet, J.P., eds., Prediction of Underwater Landslide Hazards, Balkema, Rotterdam, in press.

Boore, D.M., Joyner, W.B., and Fumal, T.E., 1997, Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: Seismological Research Letters, v. 68, p. 128-153.

Campbell, K.W., 1997, Empirical near-source acceleration relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra: Seismological Research Letters, v. 68, p. 154-179.

Clarke, S. H., Greene, H. G., Kennedy, M. P., and Vedder, J. G., 1987, Geologic map of the inner-southern California continental margin: California Division of Mines and Geology, California Continental Margin Geologic Map Series, Area 1 of 7, sheet 1 of 4, scale 1:250,000.

Crouch, J.K., and Suppe, J., 1993, Late Cenozoic tectonic evolution of the Los Angeles basin and Inner California Borderland: A model for core complex-like extension: Geological Society of America Bulletin, v. 105, p. 1415-1434.

Davis, T. L., Namson, J., and Yerkes, R. F., 1989, A cross-section of the Los Angeles area: Seismically active fold-and-thrust belt, the 1987 Whittier Narrows earthquake, and earthquake hazard: Journal of Geophysical Research, v. 94, p. 9644-9664.

Ehlig, P.L., 1977, Geologic report on the area adjacent to the San Onofre Nuclear Generating Station, northwestern San Diego County, California: unpublished report prepared for Southern California Edison Company (Rosemead), 38 p., 10 figs.

Field, M.E., and Edwards, B.D., 1993, Submarine landslides in a basin and ridge setting, southern California: in Schwab, W.C., Lee, H.J., and Twichell, D.C., eds., Submarine Landslides: Selected Studies in the U.S. Exclusive Economic Zone, U.S. Geological Survey Bulletin 2002, p. 176-183.

Fischer, P. J., and Mills, G. I., 1991, The offshore Newport-Inglewood - Rose Canyon fault zone, California: Structure, segmentation, and tectonics: *in* Abbott, P.L., and W.J. Elliott, eds., Environmental Perils of the San Diego Region. San Diego Association of Geologists Guidebook, p. 17-36.

Franklin, J.P., and Kuhn, G.G., 2000, Paleoseismic features exposed by trenching the lowest coastal terrace at Carlsbad, California: in Neotectonics and Coastal Instability, Orange and northern San Diego Counties, California, Joint Field Conference guidebook, v. 1., AAPG Pacific Section, Long Beach, California, p. 1-13.

Grant, L.B., Mueller, K.J., Gath, E.M., Cheng, H., Edwards, R.L., Munro, R., and Kennedy, G., 1999, Late Quaternary uplift and earthquake potential of the San Joaquin Hills, southern Los Angeles basin, California: Geology, v. 27, p. 1031-1034.

Greene, H. G., Bailey, K. A., Clarke, S. H., Ziony, J. I., and Kennedy, M. P., 1979, Implications of fault patterns of the inner California Continental Borderland between San Pedro and San Diego: *in* Abbott, P. L., and Elliott, W. J., eds., Earthquakes and other perils - San Diego Region: San Diego Association of Geologists Guidebook, p. 21-27.

Ingersoll, R.V., and Rumelhart, P.E., 1999, Three-stage evolution of the Los Angeles basin, southern California: Geology, v. 27, p. 593-596.

Kuhn, G., M.R. Legg, and E. Frost, 1994, Large pre-historic earthquake(s) in coastal San Diego County, California: *in* Paleoseismology Workshop Proceedings, Sept. 1994, Marshall, CA, U.S. Geological Survey Open-File Report 94-568, p. 100-103.

Kuhn, G.G., Legg, M.R., Johnson, A., Shlemon, R.J., and Frost, E.G., 1996, Paleoliquefaction evidence for large pre-historic earthquake(s) in north-coastal San Diego County, California: in Munasinghe, T. and Rosenberg, P., eds., Geology and natural resources of coastal San Diego County, California, Field-trip guidebook, San Diego Association of Geologists, p. 16-24.

Kuhn, G.G., 2000, Sea cliff, canyon, and coastal terrace erosion between 1997 and 2000: San Onofre

EX. 2 (3 OF 5)

State Beach, Camp Pendleton Marine Corps Base, San Diego County, California: in Neotectonics and Coastal Instability, Orange and northern San Diego Counties, California, Joint Field Conference guidebook, v 1., AAPG Pacific Section, Long Beach, California, p. 31-87.

Kuhn, G.G., Legg, M.R., Shlemon, R.J., and Bauer, J.L., 2000, Neotectonics in the North Coastal Area, San Diego County, California: in Neotectonics and Coastal Instability, Orange and northern San Diego Counties, California, Joint Field Conference guidebook, v. 1., AAPG Pacific Section, Long Beach, California, p. 88-103.

Lander, J.F., Lockridge, P.A., and Kozuch, M.J., 1993, Tsunamis affecting the west coast of the United States, 1806-1992: U.S. Dept. Commerce, NOAA, Boulder, Colorado.

Legg, M.R., and M.P. Kennedy, 1991, Oblique divergence and convergence in the California Continental Borderland. *in* Abbott, P.L., and W.J. Elliott, eds., Environmental Perils of the San Diego Region. San Diego Association of Geologists Guidebook, p. 1-16.

Legg, M.R., Nicholson, C., and Sorlien, C., 1992, Active faulting and tectonics of the inner California Continental Borderland: [abstract] EOS Trans. American Geophysical Union, v. 73, p. 588.

Legg, M. R., G. Kuhn, J. Johnson, and E. G. Frost, 1995, Prehistoric tsunami investigations in southern California [expanded abstract]: *in* Proceedings, Tsunami Deposits: Geologic Warnings of Future Inundation: Workshop at University of Washington, Seattle, p. 33-34.

Legg, M.R., and Kamerling, M.J., 2001, Large-scale basement-involved landslides, California Continental Borderland: in Watts, P., Synolakis, C.E., and Bardet, J.P., eds., Prediction of Underwater Landslide Hazards, Balkema, Rotterdam, in press.

Locat, J., Locat, P., and Lee, H.J., 2001, Numerical modeling of the mobility of the Palos Verdes debris avalanche, California, and its implication for the generation of tsunamis: in Watts, P., Synolakis, C.E., and Bardet, J.P., eds., Prediction of Underwater Landslide Hazards, Balkema, Rotterdam, in press.

McCarthy, R.J., Bernard, E.N., and Legg, M.R., 1993, The Cape Mendocino earthquake: A local tsunami wake-up call? in Proc. 8th Symposium on Coastal and Ocean Management, New Orleans, Louisiana, p. 2812-2828.

McCulloch, D.S., 1985, Evaluating tsunami potential: in Ziony, J.I., ed., Evaluating Earthquake Hazards in the Los Angeles Region: U.S. Geological Survey Professional Paper 1360, p. 375-413.

Mueller, K., Grant, L.B., and Gath, E., 1998, Late Quaternary growth of the San Joaquin Hills anticline: A new source of blind thrust earthquakes in the Los Angeles basin: Seismological Research Letters, v. 69, p. 161.

Nicholson, C., Sorlien, C.C. and Legg, M.R., 1993, Crustal imaging and extreme Miocene extension of the Inner California Continental Borderland: [Abstract] *in* Geological Society of America Abstracts with Programs, v. 25, p. 418.

Nicholson, C., Sorlien, C. C., Atwater, T., Crowell, J. C., and Luyendyk, B. P., 1994, Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault system: Geology, v. 22, p. 491-495.

Plafker, G., and Galloway, J.P., eds., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.

Rivero, C., Shaw, J.H., and Mueller, K., 2000, Oceanside and Thirtymile Bank blind thrusts: Implications for earthquake hazards in coastal southern California: Geology, v. 28, p. 891-894.

Sadigh, K., Chang, C.-Y., Egan, M.A., Makdisi, F., and Youngs, R.R., 1997, Attenuation relationships for shallow crustal earthquakes based on California strong motion data: Seismological Research Letters, v. 68, p. 180-189.

Somerville, P.G., Smith, N.F., Graves, R.W., and Abrahamson, N.A., 1997, Modification of empirical strong ground motion attenuation relations to include the amplitude and duration effects of rupture directivity: Seismological Research Letters, v. 68, p. 199-222.

Tappin, D.R., Watts, P., McMurtry, G.M., Lafoy, Y., and Matsumoto, T., 2001, Prediction of slump

EX. 2 (4 of 5)

generated tsunamis; The July 17, 1998 Papua New Guinea tsunami: in Watts, P.. Synolakis, C.E., and Bardet, J.P., eds., Prediction of Underwater Landslide Hazards, Balkema, Rotterdam, in press.
Watts, P., and Raichlen, F., 1994, Water waves generated by underwater landslides: [abstract] Seismological Research Letters, v. 65, p. 25.

EX 2 (5 of 5)