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(corrected for errata listed in letters of Dec. 4, 1980, Dec. 18, 1981, and June 11, 1981)

Dr. Robert E. Jackson, Chief
Geoscience Branch
Division Site Safety and Environmental Analysis
Washington, D.C. 20555

Dear Dr. Jackson:

During the period, May 1979 to present, I reviewed reports, maps, responses to questions, and other data that relate to seismic design parameters for the San Onofre Nuclear Generator Units 2 & 3 (SONGS). The main purpose of my review is to evaluate evidence on the seismotectonic setting and methods for estimating the maximum earthquake on the Offshore Zone of Deformation (OZD). My evaluation includes:

(1) Review of the numerous reports, publications, maps, and Landsat imagery of the southern California-Baja California region for information on the seismotectonic setting of the site and the OZD.

(2) Study and appraise the methods used for determining the maximum earthquake to be expected for the OZD, including a careful rechecking of the source data utilized and rationale that forms the basis of the new fault-slip-rate method proposed for the first time in Woodward-Clyde Consultants (1979).

(3) Examine seismologic and geologic evidence that defines the basic fault parameters of the OZD and in turn, affects the maximum earthquake magnitude for this fault zone.

I am impressed with the quantity and quality of the studies and data base that have been assembled for the evaluation of the OZD and its seismic potential. The types of study are appropriate

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and represent state-of-the-art methods. The seismic reflection profiles and the subsurface electric logging data confirm the OZD to be an active or capable fault zone. The geophysical interpretations of the offshore reflection profiles and the subsurface analysis of the Newport-Inglewood Zone of Deformation (NIZD) provide a basis for analysis of the OZD and its seismic potential. The Woodward-Clyde Consultants (WCC) study of the worldwide strike-slip fault data, and the methods by which this data can be applied to the OZD is carefully and thoroughly prepared in the WCC (1979) report and in the Responses to the NRC Questions (361.38, 44, 45, 46, 47, 48, 50, and 51) submitted by Southern California Edison Company (SCEC) and San Diego Gas and Electric Company (SDG & EC). The main body of data is summarized in the following reports:

Woodward-Clyde Consultants, June 1979, Report of the evaluation of maximum earthquake and site ground motion parameters associated with the Offshore Zone of Deformation, San Onofre Nuclear Generating Station: Woodward-Clyde Consultants, 30 p. with tables, and Appendices A to J.

Southern California Edison Company, and San Diego Gas & Electric Company, 1980, San Onofre Nuclear Generation Station Units 2 & 3, Responses to NRC Questions 361.37 through 361.62.

______, 1980, San Onofre Nuclear Generating Station Units 2 & 3, Responses to NRC Questions 361.63 and 361.64.

______, 1980, San Onofre Nuclear Generating Station Units 2 & 3, Addendum to response 361.63.

______, 1980, San Onofre Nuclear Generating Station Units 2 & 3, Responses to NRC Questions 361.66 through 361.68.

In addition to the study of these documents and their supplemental sources of data, I have examined more than 150 papers that discuss regional tectonics, geology, seismicity, and worldwide data on fault characteristics, parameters, and associated earthquake magnitudes. The new methods proposed in the WCC and the SCEC - SDG & EC analyses were rechecked by evaluating the accuracy and scope of the data base, studying critical papers in the general literature, and using my personal familiarity with much of the source data, including visits to many similar faults that are

pertinent to this review (southern California, Alaska, Japan, New Zealand, and South America).

My analysis is primarily based on the earthquake magnitude in relation to fault rupture length, maximum displacement, earthquake recurrence, slip rate, and sesimotectonic setting. In addition, I have reviewed the subsurface data for the Newport-Inglewood Zone of Deformation (NIZD), the geophysical studies of the South Coast Offshore Zone of Deformation (SCOZD) and the Rose Canyon Fault Zone (RCFZ).

I concur with the broad-based, multi-method approach presented in the WCC report of June 1979 and in the Responses to Questions. The applicants documentation is a thorough and generally accurate appraisal of the field and geophysical data for the Offshore Zone of Deformation (OZD), a broad zone of faulting and secondary folding between the Santa Monica fault and San Diego Bay. My initial questions about the applicability of the new slip-rate method, including some of the field data and interpretation, have been resolved in responses to subsequent questions. Although the geologic setting is very complex and the question of total fault length is not completely resolved, I believe that the present information provides an adequate base for making decisions on the maximum earthquake parameters for the OZD and their effect on the SONGS site.

I was initially critical of the new fault slip rate method because of omissions and errors in original data base and the exclusion of the normal-slip and reverse-slip data. I now believe that the recent responses to questions include accurate and complete data and justify the exclusion of data from normal-slip faults, reverse-slip faults, and Japan. I now believe that fault-slip-rate method is the most quantitative approach for state-of-the-art assessment of the maximum earthquake for the OZD.

My review considers the following topics in order of decreasing importance, weight, and reliability in establishing the maximum earthquake magnitude:

(1) Fault Capability

(2) Fault Slip Rate

(3) Fault Rupture Length

(4) Total Fault Displacement

(5) Degree of Deformation

(6) Maximum Historic Earthquake

(7) Maximum Surface Displacement

FAULT CAPABILITY

The capability of the OZD according to the definition of U.S. CFR Part 100 (1975) is indicated for the NIZD by Pleistocene offsets of alluvial materials (Barrows, 1974), stream channels (Castle and Yerkes, 1976), and shallow faulting noted in oil fields along the fault zone (WCC, 1979, Appendix A, p. A-5 and A-9). The right-slip style of faulting on the NIZD appears to be related to wrench faulting with a north-south compression axis and uniform rate of deformation for at least the last 8 my (WCC, 1979, figs. 4 and 5; Harding, 1973; Yeats, 1973). The capability is shown for NIZD by the 30 km long segment that ruptured in the basement rocks (WCC, 1979, figs. E-7 and E-8) with a shallow focus (10 km), and a right-slip mechanism (WCC, 1979, figs. E-5 and E-10) during the Long Beach earthquake of 1933 (M=6.3).

Capability of the SCOZD is indicated by: (1) ponding of low velocity Quaternary sediments on the landward side of faults and folds of the OZD, (2) projection of faults to the sea floor shown by many seismic reflection profiles (SCE, 361.63), and (3) general continuity, parallelism, and similarity of fault and fold pattern to the NIZD.

Capability of the RCDZ is suggested by several late Quaternary to possible Holocene right-slip faults (Kennedy and others, 1975, with a dated offset of 100,000 yrs; Kern, 1977, with a date of 80,000 to 100,000 yrs; and Liem, 1977, with a dated offset of 28,700 yrs). These dates are summarized in Table C-1 of WCC (1979).

The northern terminus of the OZD is at the intersection with the capable Santa Monica fault zone. Possible connections to the south include: (1) offshore connections from San Diego Bay to Aqua blanca fault zone (Legg and Kennedy, 1979), which has late Quaternary offsets (Allen and others, 1960; Gastil and others, 1975), or (2) en echelon connections with the Calabasus fault (Gastil and others, 1975, 1979; fig. 361.66-1, no. 6), a fault that appears to be capable, the longer Vallecites fault that does not appear to be capable, and the San Miguel fault zone (Shor and Roberts, 1958; Gastil and others, 1979) that has historic surface faulting.

FAULT SLIP RATE

The geologic slip rate method is the primary basis used in the WCC (1979) report and the response to questions 361.38 and 361.45 to determine the maximum earthquake value for the OZD (fig. 7 of WCC, 1979; and questions 361.45-1, 361.38-4). The initial data base, the first compilation of its kind, is in Figure 7 of WCC, 1979, and with extensive revisions, is described in response to questions 361.44, 45, 46, 47, 48, 50, and 51, and shown in Figure 361.45-2 (with error boxes) and Figures 361.45-2 and 361.38-4 (with proposed limiting lines).

The analysis includes up-to-date published data and, although future earthquakes or new investigations may add new data points or modify old data, the new analysis is accurate, thorough, and state-of-the-art. My review of the data, including Appendix B of WCC (1979), and about 20 percent of the electric log correlations, supports the fault slip rate for the NIZD at 0.5 mm/yr, with a low likelihood that the new data will change this value by greater than 15 percent. The analysis of the worldwide slip rate data, including geologic offsets as a function of time, is accurate and thorough. These data control the line, bounding extremes of bracketed ranges of data (MEL of figure 361.38-4). The probable limiting boundary for a slip rate of 0.5 mm/yr is 6.3, as defined by the line bounding maximum observed historical earthquakes (MEL). The most

conservatively defined line bounds extremes of the bracketed ranges of data by using the extreme corners of the error boxes for present data and suggests a maximum magnitude of about 6.85. The data base for these figures is based on a very short historic record of earthquake activity; future earthquakes and newer data are likely to extend the limits to some indeterminately higher value. Accordingly, I believe that to assure conversatism in analysis, the limiting line for maximum magnitude should be shifted to the right to indicate a maximum earthquake for the NIZD, with 0.5 mm/yr slip rate, to about 7 magnitude. This is an upward shift of about 0.7 magnitude from the probable maximum magnitude of 6.3 and about 0.15 from the extreme corner of the bracketed range at 6.85 magnitude. This assignment of 7 magnitude provides an additional degree of conservatism to allow for:

(1) The possible short-term perturbations from an overall 0.5 mm/yr slip rate of the NIZD, which is assumed to also apply to the Southern California Offshore Zone of Deformation (SCOZD) and the Rose Canyon Fault Zone (RCFZ).

(2) the probably inaccurate nature of some published data, and

(3) the deficiency in available data for faults with low slip rates (e.g., less than 1.0 mm/yr).

FAULT RUPTURE LENGTH

General Comments

Earthquake magnitude versus surface fault rupture length relationships are summarized by Tocher (1958), Iida (1959 and 1965), Bonilla (1967 and 1970), Bonilla and Buchanan (1970), Mark (1977), Mark and Bonilla (1977), and Slemmons (1977). The theoretical basis for the correlation between size of earthquake and fault rupture length is based on Tsuboi (1956), who related seismic energy release to an earthquake volume (length, width,

and thickness of the elastically strained material) to both fault rupture length and amount of fault displacement. The use of empirical correlations of earthquake magnitude versus surface rupture lengths, measurements of geodetic deformation or surface displacement is possible where brittle failure or surface deformation from shallow focus earthquakes occurs in surficial materials.

Direct application of the fault rupture length to magnitude of shallow focus earthquakes requires that the total surface rupture length can be observed. The method is difficult to apply where plastic deformation and/or drag conceals the primary tectonic effects, where bodies of water or other surficial materials conceal the fault surface rupture, or where the fracture patterns form complex distributed systems (Slemmons, 1977; Bonilla, 1979). For such cases, additional subsurface geologic data, geodetic deformation data, aftershock distribution maps, or other geophysical or seismological analyses may be required.

Indirect methods can be applied by using subsurface information or by using fractional fault rupture length data as suggested by Albee and Smith (1966) and Wentworth, Bonilla and Buchanan (1969). This method is in wide use, although it is not always possible to accurately delineate the total length of a fault (Slemmons, 1977; Bonilla, 1979).

Direct Method

The use of the direct method of application of the fault rupture length versus magnitude, or the maximum surface displacement versus magnitude is not possible for the OZD, as surface faulting is rare along the zone. Displacements are normally in the form of plastic deformation of shallow, late Tertiary surficial sediments.

Indirect Method by Fault Segment Lengths

The surface rupture length versus earthquake magnitude relationship can be applied to the OZD by assuming that the zone is segmented, and that the segments are indicated by the length of the main ruptures of the deeper sediments as indicated by displacements on the reflector zones, B and C (figs. D-1 and D-2 of WCC, 1979). This method assumes that the continuity of the fault at depths is defined by lengths of ruptures that cut either the B or C zone. The B and C zones, are respectively, correlated with a post-Miocene unit (about 5 my BP) and the lower to middle San Onofre Breccia units (about 8 my BP). The application also assumes that the subsurface maps of faults cutting reflectors B and C are accurate and that the gaps between fault segments are well-defined. My suggested analysis will require modification if newer maps differ from the reflector profile maps of WCC (1979).

A discontinuity between segments is defined by Horizon B at the break shown in Figure D-2 of WCC (1979), about 35 km NNW of San Onofre near a change in the en echelon and branching patterns (shown in fig. D-1 of WCC, 1979). The fault segment extends south from this area with the southern end at the branching pattern about 10 km WSW of San Onofre. The total length of this segment is 40 km. Another segment extends for 37 km length northward from the onshore segment of RCFZ. These fault segments provide the following estimated magnitudes for a full rupture length of the segment using the relationship for strike-slip faults of Slemmons (1977) of $M_S = 0.597 + 1.351 \log_{10} L$ (in m):

ASSUMED RUPTURE LENGTH		M_S
OZD	(40 km length)	6.8
RCFZ	(37 km length)	6.8-

A more conservative approach defines the fault segment lengths on the basis of Horizon C. An assumed length is defined on the south and by an inflection point at a break in continuity as shown in Figure D-1 of WCC (1979), the point of marked change in fault strike about 27 km SSE of SONGS, and to the north at the change in rupture pattern and junction with transverse faults about 35 km NNW of SONGS. The total length of this fault segment is 62 km. The relationship for strike-slip faults of Slemmons (1977) indicates the following earthquake magnitude:

ASSUMED RUPTURE LENGTH		M_S
SCODZ	(62 km length)	7.1-

A third estimate of earthquake magnitude is derived using the values listed in the response to Question 361.66 (Table 361.66-1) with lengths of 36 km for the NIZD, 27 km for the SCOZD, and 48 km for the RCFZ; the criteria for assigning these lengths is not described. Using the strike-slip fault relations of Slemmons (1977), the following magnitudes are estimated:

ASSUMED RUPTURE LENGTH		M_S
NIZD	(36 km)	6.7+
SCOZD	(27 km)	6.6-
RCFZ	(48 km)	6.9

The above calculations suggest a maximum earthquake for the OZD of 6.5 to 7.0- and, in my opinion, are "soft" values, subject to debate. Accordingly, although these values are considered in this overall analysis, a low weighting is placed on their reliability.

Indirect Method by Fractional Fault Length

The use of an assumed fractional fault rupture length, based on the total fault length is proposed for southern California by Wentworth and others (1969), with a statement that for all slip-type faults in North America, the historic earthquakes have broken lengths of from 2 percent to more than 75 percent of the total fault length. Since 1969, this method has become widely used for evaluation of active strike-slip faults with known lengths, and the assumed rupture length is generally taken at one-half, one-third, or one-fourth of the total fault length to provide a maximum probable earthquake. The length that is determined from the fractional length is then assumed to be the surface rupture length and the M_S magnitude is determined by use of the appropriate rupture length versus magnitude regression equation, or by interpolation from the corresponding graph of Slemmons (1977) or Mark and Bonilla (1977).

In order to apply this method to the OZD, the worldwide data base for strike-slip faults should be reviewed to determine which fraction or percentage of the total fault length should be used. My review of the data uses the following rationale for the basic percentages to be used.

Rationale for Estimation of Total Fault Length

1. Length of many faults are defined, or have been suggested in various publications.
2. Faults are generally terminated by cross-cutting faults, or a branching relationship from a fault with a higher slip or strain rate, or by connection to plate tectonic boundaries. For example, the Hayward fault branches from the Calaveras fault, which branches from the San Andreas fault zone, which connects to the Gulf of California spreading center and to the Mendocino fault.
3. Faults of similar style or rate of deformation are assumed to be connected if they are on strike and are separated by short data gaps, are covered, or appear to have an en echelon relationship.

4. Faults with high slip rates and amounts of displacement cannot die out abruptly without terminating against a bounding structure, or connecting with a major causative plate tectonic feature.
5. Faults may gradually die out away from the causative tectonic structure by decreased slip rate, decreased displacement, or change in style of deformation (folding).

The mean percentage of rupture length versus total fault length or fault zone length for available worldwide data is 22 with a standard deviation of 7. This suggests that the typical strike-slip rupture during larger earthquakes is about one-quarter of the total fault length or fault zone length.

Observed Fault Rupture Lengths for Strike-Slip Faults

Historic surface rupturing on major strike-slip faults have the following observed, or inferred fault rupture lengths during earthquakes exceeding M_S=6 (see table that follows).

Application to the OZD

1. OZD with a Length from Santa Monica Fault to San Diego Bay:

The field data supports a total fault zone length measured from the northern, truncating Santa Monica fault to the San Diego Bay area for a length of 190 km, or a 22 percent length of 42 km. The northern limit is a truncating capable or active fault. The southern limit corresponds to a point of changed tectonic style to prominent normal faulting. Evidence for continuity between the OZD and faults to the south is inconclusive. Using the 22 percent length value derived above, this corresponds with a surface rupture length of 44 km, and an earthquake of M_S=6.9 or using one standard deviation (30 percent) for a length of 57 km, M_S=7.0.

2. Connections to the Coronado Banks and/or the Agua Blanca Fault Zone:

Possible continuity with the Agua Blanca has been suggested by an en echelon system connecting to the Coronado Banks and ultimately to the Agua Blanca fault zone. Evidence for this connection is poor and lacks documentation but is suggested in the map of Legg and Kennedy (1979) and Figure 361.40-1. Such a connection would require a change in strike at San Diego Bay with a possible change

from purely strike-slip faulting on the OZD to prominent normal faulting components at San Diego Bay and perhaps to Coronado Banks. If such a connection exists, the total length between the Santa Monica fault and the Coronado Banks fault is 250 km. Further extension to the Agua Blanca fault is approximately 300 km. For a 22 percent rupture length of 250 km (35 km), this would indicate an earthquake of M_S=7.0 and for 22 percent of a 275 km length (61 km) to the Agua Blanca for a calculated magnitude of 7.1-. Addition of one standard deviation (a total of 30 percent fault length) would yield 75 km length for the OZD including the segment to the Coronado Banks fault, for a calculated magnitude of 7.2-. For inclusion of the Agua Blanca fault a 30 percent length (83 km) yields a magnitude of 7.2.

If the OZD extends to the Agua Blanca fault, the branching relation, the different strike, and the possibly different slip mechanism suggest that it should be considered separately from the Agua Blanca fault; worldwide data on branching faults suggests major rupture on one does not immediately cause major rupture on the other. Accordingly, the 250 km length appears to be an extreme length assumption.

3. <u>Connection to the Calabasas, Vallecitos and San Miguel Faults</u>:

The southeastward connection to the San Miguel fault zone does not appear to be likely, due to: (1) lack of both photogeological evidence and field evidence for continuity (Gastil, Kies and Melius, 1979), (2) some major faults (Vallecitos), of this zone lack geomorphic evidence for activity, (3) geologic units do not appear to have substantial strike-slip offsets, and (4) apparent decrease in activity across the zone east of the San Miguel fault. Additional evidence against this proposed connection is summarized in the NRC answers to the interrogatories by Friends of the Earth (October 17, 1980). This suggests that the San Miguel zone does not connect directly to the OZD, or if deep continuity exists, it is reasonable to interpret this zone in terms of separate, partly en echelon, individual faults with very low slip rates and low activity that may be activated independently, and the length of the zone should not be added to that of the OZD.

Table of major strike-slip faults, with estimated total length, and percent of fault ruptured during earthquakes of about $M_S = 6$ or greater.

FAULT, DATE	M_S	TOTAL LENGTH (KM)	RUPTURE LENGTH (KM)	PERCENT OF LENGTH
San Andreas		1380		
1857	8.25		370-400+	29.0
1906	8.25		435	31.5
North Anatolian				
1939	7.9		350	26.9
1942	7.3		50	3.8
1943	7.6		265	19.9
1944	7.4		190	14.3
1957	7.1		40	3.0
1967	7.1		54	4.1
Fairweather-Queen Charlotte		1150		
1899	8.5?			
1949	8.1		380	33.0
1958	7.9		350	32.6
1972	7.1		170	15.8
Montagua		1100+		
1976	7.5		230-240	21.4
Awatere-Wellington		547		
1948	7.1		100?	18.3?
Clarence-West Wairarapa		600		
1855	7.5		160	26.7
Hope-East Wairarapa		410		
1888	6.7		55	13.4
San Jacinto-Cerro Prieto (incl. Coyote, Superstition Mtns., Superstition Hills and Imperial faults		290		
1934	7.1		?	
1940	6.7		64	22.1
1968	6.4		33	11.4
1979				
Calaveras-Green Valley		272		
1861	6		29	10.7
1979	5.9		16	8.4
Hayward-Rodgers Creek-Healdsburg		285		
Maacama	6.7		48	16.8

The mean for highest percentage on each fault (underlined) = 22.1
Standard deviation = 7.45

TOTAL FAULT DISPLACEMENT

This method is used by WCC (1979) to assist in the qualitative comparison of features as noted in the initial paragraph of the response to question 361.38, and is presumably based primarily on the data of Table G-1, and Table 361.45-2.

For greatest offset during late Tertiary, the following values are tabulated:

		Age (my)	Displ. (km)	Max. M_S
1	San Andreas (northern section)	1-5	30	8.3
2	San Andreas (central section)	ca. 5	80	8.25
3	San Andreas (southern section)	10	215	6.5
4	San Jacinto	0.73-	5.7-8.6	7.1
5	Elsinore	2?	5	5.5-6
6	Whittier	2?	2.5	4.2
7	NIZD	3	5?	6.3
8	Calaveras-southern	3.5	11-27	5.3
9	Calaveras-Sunol	5?	4.8	5.3
15	Bocono	5	50	8
16	Hope	5+?	20	6.7
19	N. Anatolian	15	85-95	7.9

The above data only provide a qualitative measure for a maximum earthquake that is suggestive, but is not definitive of, a magnitude. Slip rate provides a similar measure and simultaneously considers displacement and changes in rate of displacement with geologic time.

DEGREE OF DEFORMATION

The degree of deformation is difficult to evaluate in southern California because major surface scarps are poorly developed in the OZD zone of plastic deformation. Although geomorphic expression of the NIZD is inconspicuous or local, the associated wrench fault style of folding is well developed. These features are difficult to directly correlate with other faults where brittle failure occurs at the surface and scarps and associated landforms are inconspicuous. I conclude that the degree of deformation of deposits and development of landforms is difficult to assess for the OZD because of the partial water, or ductile sediments cover portion of the zone, and the dissimilar nature of rupture in comparison with many other southern California active faults.

MAXIMUM HISTORIC EARTHQUAKE

The maximum historic earthquake is 6.3 along the NIZD section of the fault zone. If it is assumed that the fault zone extends to the San Miguel fault in Baja, California, the maximum earthquake would be the 1956 earthquake of magnitude 6.8, but this assumption is problematic due to uncertainty of a connection and uncertainty of similar mechanisms. I conclude that although the maximum historic earthquake for the zone is 6.3, it is likely the maximum possible earthquake is greater for longer periods of observation. This line of evidence cannot be used to indicate maximum possible or maximum probable earthquakes because of the short historic record.

MAXIMUM SURFACE DISPLACEMENT

There is no stratigraphic or geomorphic evidence to indicate the maximum surface displacements along this zone and hence, the related maximum magnitude. The lack of conspicuous scarps in the NIZD sector may infer small displacements during the late Quaternary. The plastic deformation of the Tertiary sediments, with a wrench fault style of deformation, precludes using this method for the OZD. I conclude that this method cannot be applied to the OZD with current data.

CONCLUSIONS

1. The studies for the SONGS site are accurate, represent state-of-the-art methods and form an adequate basis for evaluating the seismic potential of the OZD.

2. The use of the fractional fault length method suggests a maximum magnitude of about $M_S=7$.

3. The most quantitative method for estimating the earthquake magnitude is the fault-slip-rate method proposed in the WCC report as modified in subsequent responses to questions. The method is new and untested by use and review by the geologic and seismologic community. I recommend that the maximum earthquake be increased from the 6.3 to 6.5- range as shown in Figure 361.38-4 to about magnitude 7 for earthquakes generated along strike-slip faults with a slip rate of 0.5 mm/yr.

4. The best method of estimating the maximum earthquake magnitude for the OZD is a general, balanced, multi-approach, as used in the WCC report and as modified in the subsequent responses to questions by the applicant.

5. Using a general, balanced, multi-approach, and my study of the OZD in relation to the worldwide fault data for historic surface rupture on active faults, their geomorphic expression, and their general character, the available evidence indicates that the maximum earthquake to be expected for the OZD is approximately $M_S=7$.

6. My evaluation of the various methods of estimating the maximum magnitude earthquake for the OZD has included an additional degree of conservatism to that of the WCC (1979) report and the responses to questions 361.37 to 361.68.

The above review provides my professional judgement of the seismic potential for the OZD. If you require further details, or wish a response to other related issues, please contact me.

Sincerely,

David B. Slemmons

David B. Slemmons
Consulting Geologist