

ANATECH CORP.



A  **Structural Integrity Associates, Inc.**® COMPANY

Robert T. Sewell, Ph.D.
Associate

A Hazard and Risk Analysis Perspective on: **Tsunami Safety Evaluation for the Diablo Canyon Power Plant**

Public Meeting of the
Diablo Canyon Independent Safety Committee (DCISC)
June 21, 2016
Avila Beach, CA

www.ANATECH.COM
www.STRUCTINT.com
877-4SI-POWER

Presentation Contents

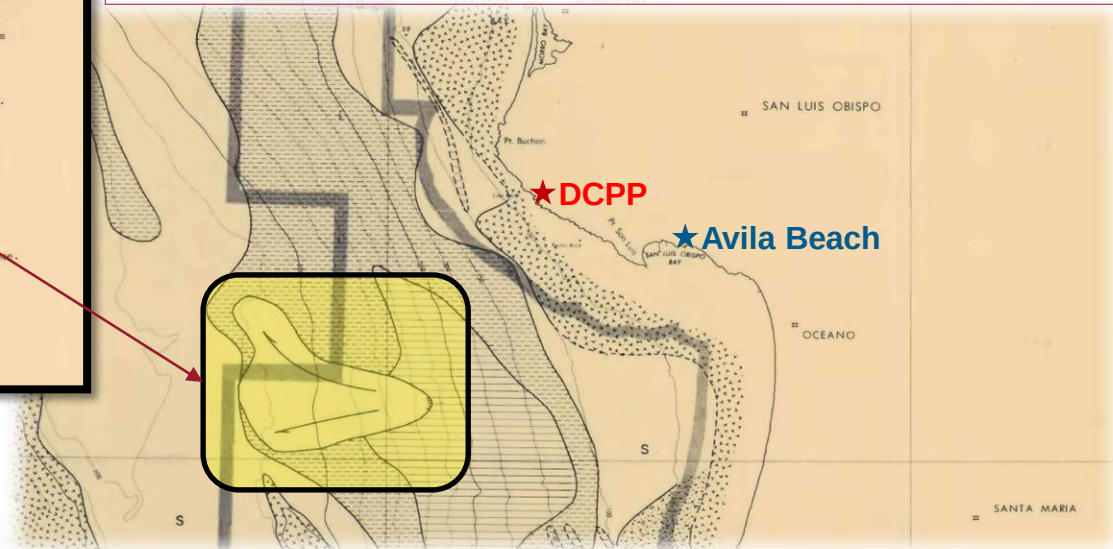
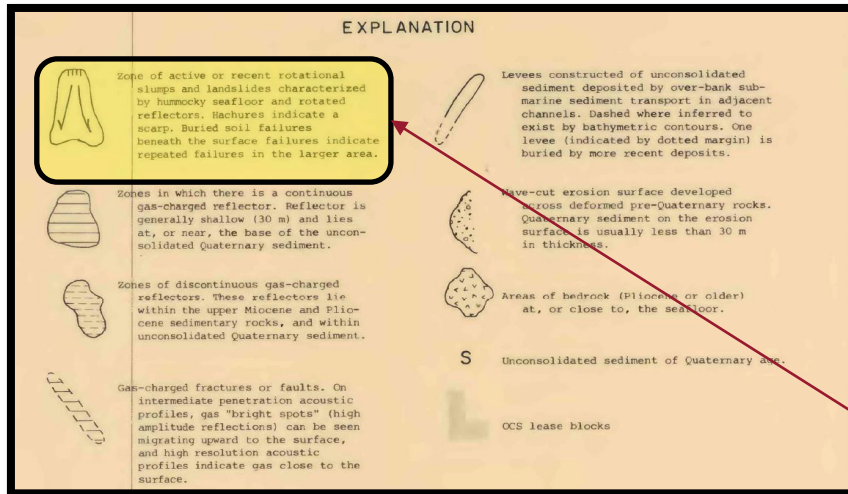
- Some Background
- Perspective on the Sewell (2003) Report
- Perspective on Recent PG&E Studies
- Some Relevant Fallacies
- Updated Recommendation and Discussion

Appendix: Additional (Back Up) Slides

Background

USGS Open-File Report; Bartlett Data

"In this seismically active area earthquake induced ground motion remains the likely candidate to supply the initial energy necessary for failure."



Revealed past slides, including a geologically "recent"* "large" slide (125 km²), believed to be progressive, in offshore Santa Maria Basin

- "The slope of the failure zone or surface is about 1.2°. Slumps and slides occur on similar gentle slopes in Eel River Basin, ..."
- "The cause of the slide in the offshore Santa Maria Basin is not known. No samples of the slide material have been collected, thus the mechanical properties of the sediment are not known."
- Creates a favorable structure for slide activation by seismic and/or gas hydrate initiator

*Note: "... sliding was sufficiently recent that sedimentation and/or erosion has not had time to mask the slide topography" ... which can be interpreted as likely order [~O(•)] of 100's to perhaps even some few 1000's years recent; or possibly, progressively active through that time, at low dynamics, up to and including current time.

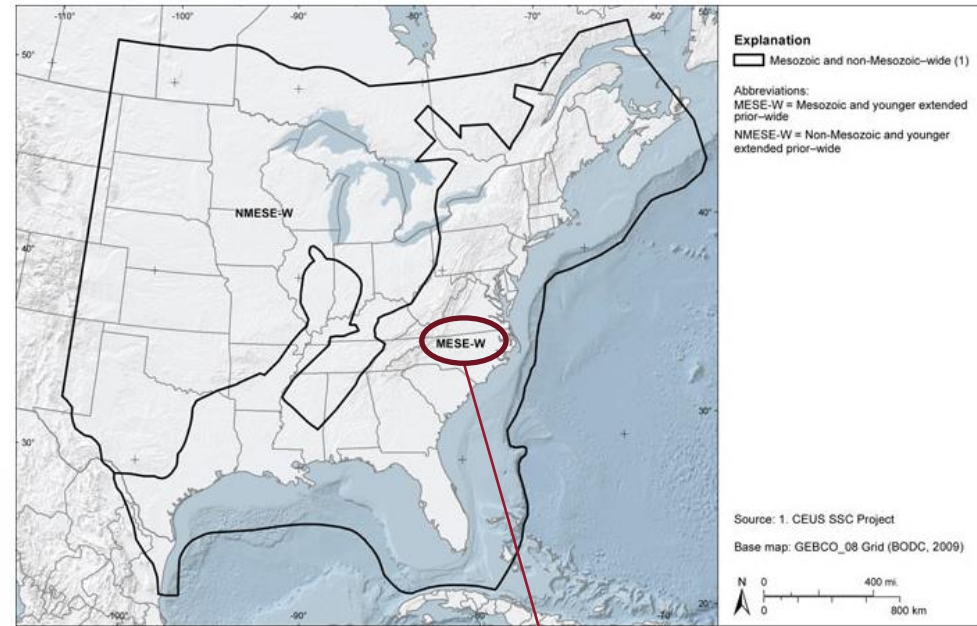


Charleston Earthquake Issue

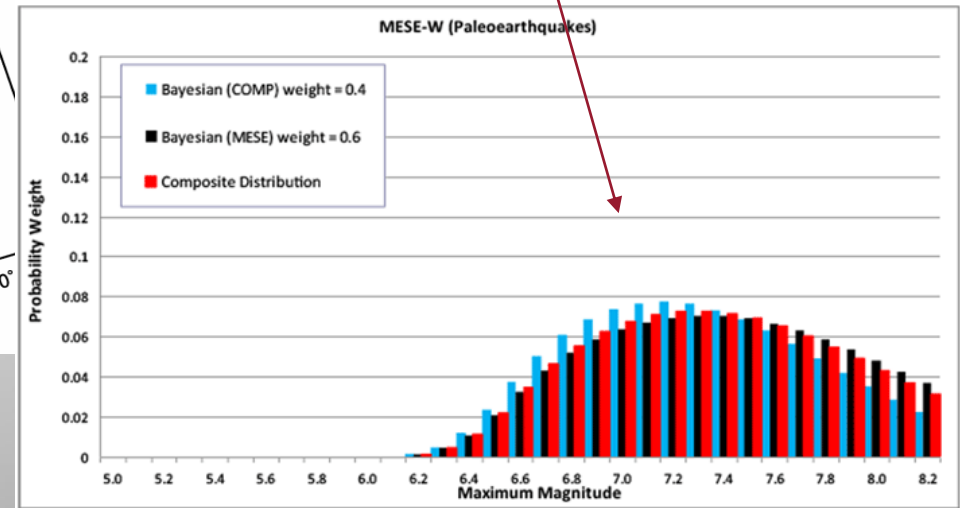
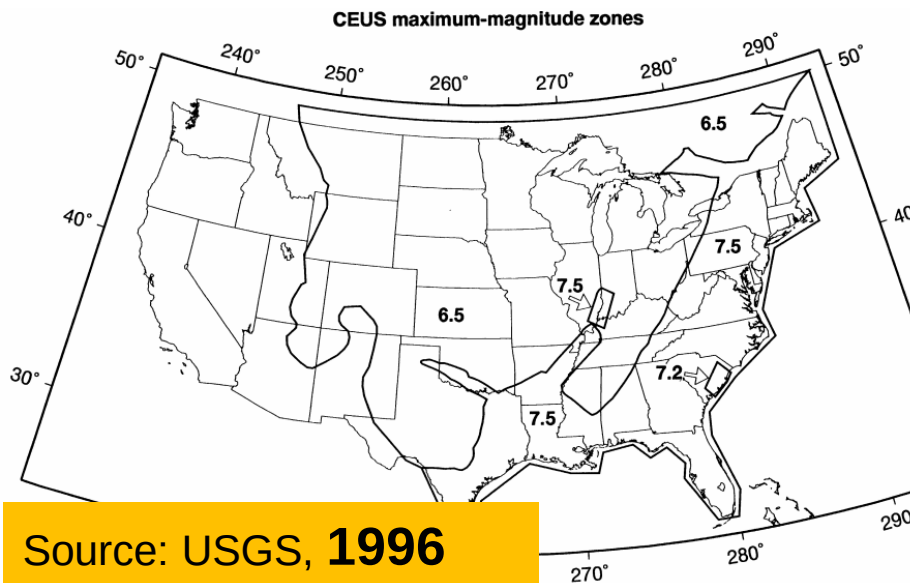
- A new state of the art in hazard and uncertainty assessment for critical facilities began to emerge from EPRI and LLNL PSHA studies:
 - Multiple experts evaluating credible competing hypotheses held by the expert community
 - Large events must be considered with suitable likelihood/weights where they cannot be systematically and conclusively ruled out by the expert community
 - Now, assessments/hypothesis of maximum magnitude (M Max) values for the central and eastern US (CEUS) range from about M 5.4 to M 8.2, depending on the specific region under consideration
 - Focus is on assessing not just central estimates of hazard, but the full uncertainty distribution of the hazard – the center, body and range (CBR)
 - Results of hazard analysis are compatible with probabilistic risk assessment (PRA)
- **Implications to Tsunami Hazard Assessment:**
 - Multi-expert, multi-disciplinary effort that must represent the expert community
 - Large source events considered where they can't be conclusively ruled out by the ITC
 - Aim must be to develop the entire uncertainty distribution (i.e., CBR of hazard)
 - Critical Value of SSHAC Methodology

Charleston Earthquake Issue

- Trend over time has gone to increased recognition among the ITC of larger Mmax values (often, also larger hazard).
- Prior Mmax distributions, which are based on global Mmax data, are generally evaluated and given some weight.
- **Analogous to appropriate treatment of maximum parameters (e.g., maximum SMF volumes) in PTHA.**



Source: CEUS Model, **2015**; EPRI 3002005684



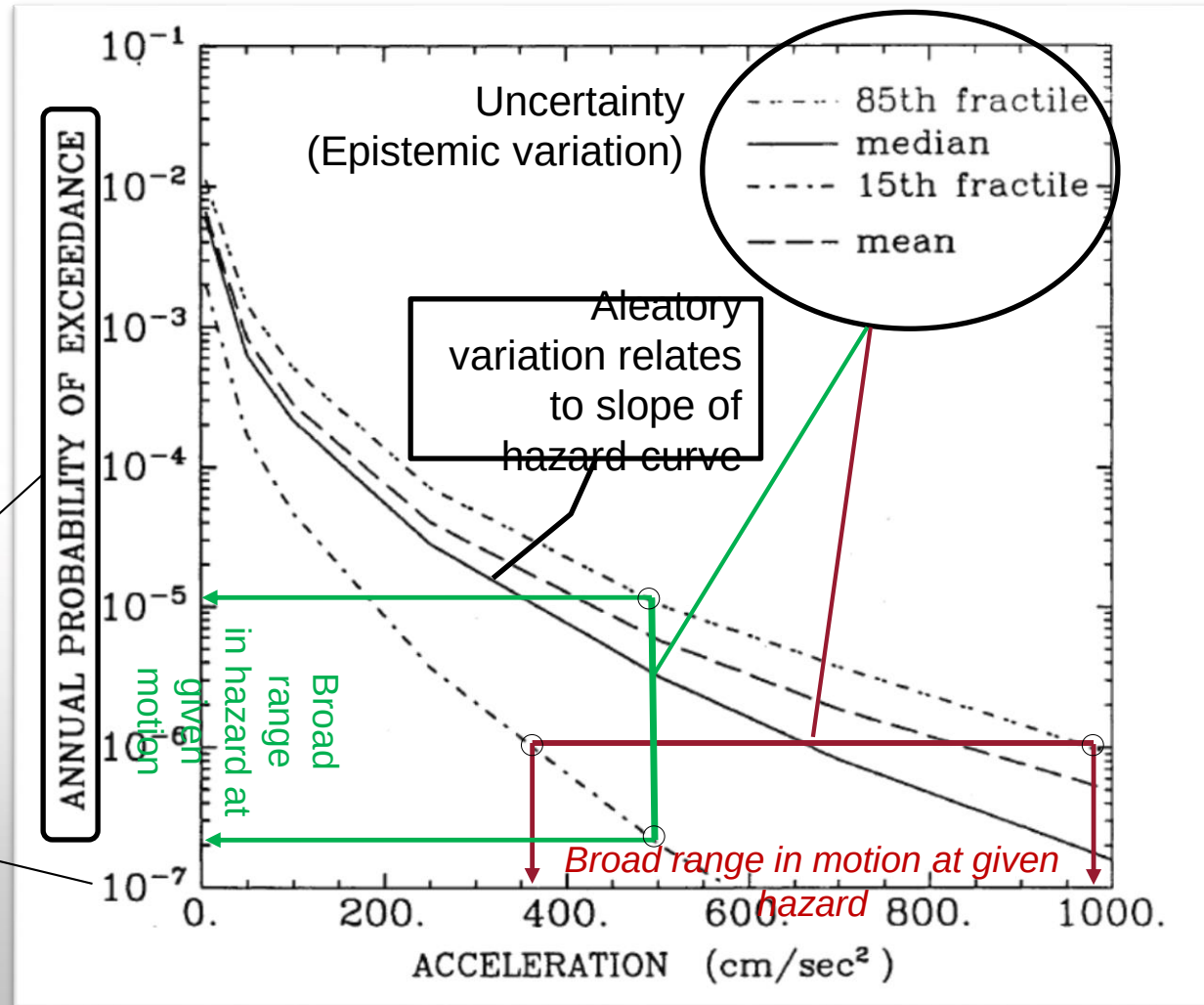
Charleston Earthquake Issue

- Example Site-Specific PSHA Result from EPRI Study (1989)

- Hazard curves are “tails” of a complementary cumulative probability distribution
- **Tsunami hazard results can be similarly conveyed**

Hazard measured as annual exceedance probability

Hazard curves extend to $10^{-7}/\text{yr}$



Source: EPRI NP-6395-D (1989)

1998 Papua New Guinea Earthquake and Landslide Tsunami

- “The Papua New Guinea (PNG) tsunami of July 1998 was a seminal event because it demonstrated that relatively small and relatively deepwater Submarine Mass Failures (SMFs) can cause devastating local tsunamis that strike without warning.”
– *Tappin, Watts and Grilli, 2008*
 - SMF was a slump having width of ~ 4.2 km, a length of ~ 4.5 km, and a thickness of ~ 750 m. The slump volume is estimated to be around 6.4 km^3 .
 - Observation suggests at least 15 m (~ 50 ft) peak run-up.
 - Model estimates of potential peak run-up are at nearly 22 m (~ 72 ft)

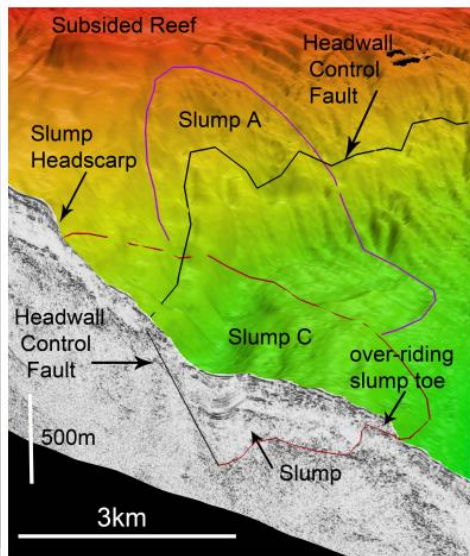


Fig. 3. 3-D image of the Amphitheatre, including seismic cutaway of slump C, viewed from the northeast. The headwall of the slump coincides with a control fault. This fault channelled artesian water pumped up from depth to the slump failure surface, triggering the slump itself around 12 min after the main shock. Vertical exaggeration 3x. See text for discussion.

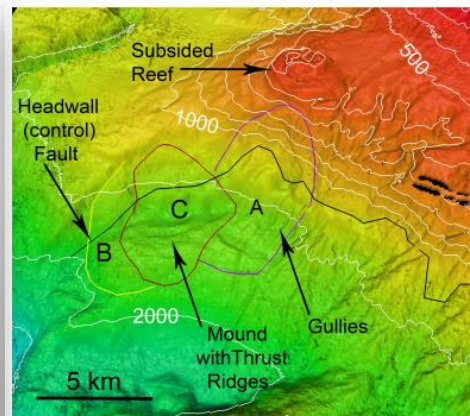
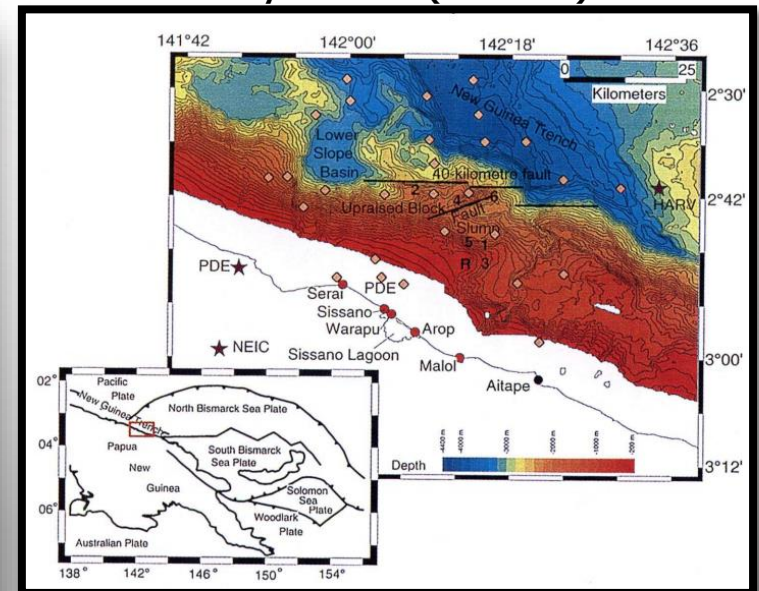


Fig. 2. 3-D image of the Amphitheatre viewed from the northwest. The three slumps (A, B and C, labelled by decreasing age) are identified together with the control fault at the base of the headscarp. Note the change in seabed morphology from the heavily gullied area in the right of the image (slump A) to that to the left (slumps B and C), where gullies are absent. Water depths are in metres. Vertical exaggeration 3x. See text for discussion.

Tappin, Watts and Grilli, 2008



Tappin, 1999.

Perspective on Tsunami Safety Evaluation of DCP **SLIDE 8**

1998 Papua New Guinea Earthquake and Landslide Tsunami

- In relation to size descriptions of submarine landslides / SMFs, note that Tappin, Watts and Grilli (2008) describe the 6.4 km³ PNG SMF as “relatively small”.
 - The recent Goleta SMF (with significant slide and tsunami generation occurring as recently as 1812) in the Santa Barbara Channels was much less, at 1.51 km³.
- Some past single-event SMFs are known to be as large as many 1000's of km³, and past event complexes have size up to about 20,000 km³ [Agulhas Slide, SE Africa]

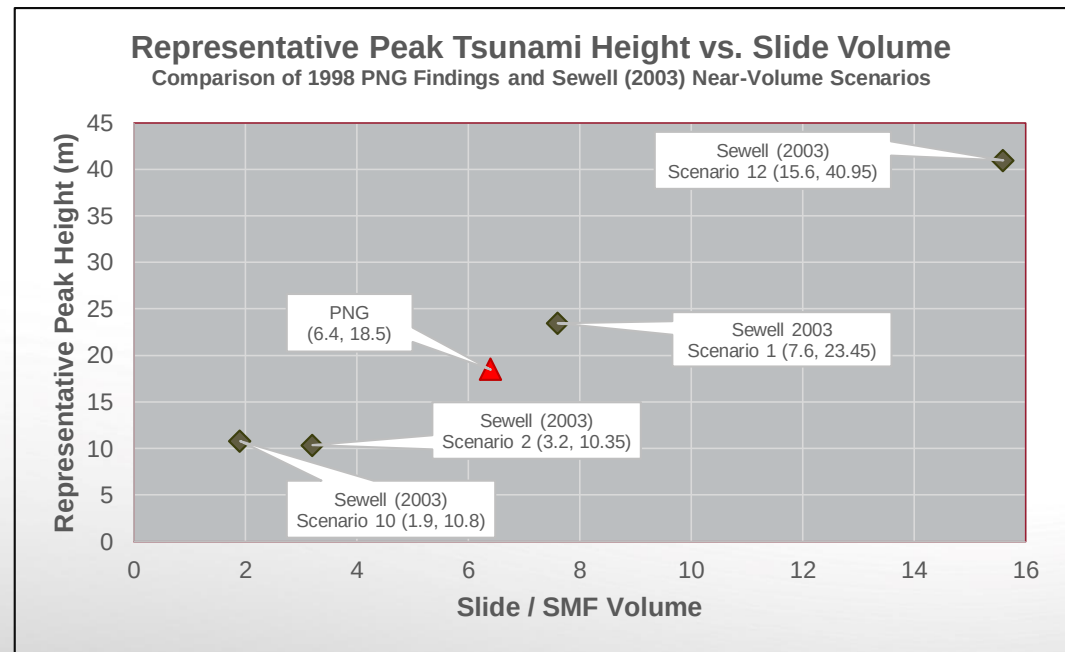
1998 Papua New Guinea Earthquake and Landslide Tsunami

- The PNG tsunami was also pivotal within the Tsunami ITC because it was controversial and eventually drew much greater attention to SMFs / submarine landslides as an important tsunami generating mechanism, and the possibility to numerically model such scenarios
- The validity of this type of scenario was clarified, as well as the need to study the potential and effects of SMF scenarios in tsunami hazard assessment, up to the maximum scenarios supported by geological conditions

Sewell (2003) Scenarios and the 1998 Papua New Guinea Tsunami

- In relation to SMF scenario development in Sewell (2003): the following comparison (albeit simplified) – of peak-wave run-ups from 1998 PNG and reported peak wave amplitudes [Table 2; Sewell (2003)] at the DCPD site – is made:

Scenario	Volume (km ³)	Peak Wave Amplitude (m)
1998 PNG	6.4	15 to 22
Scenario 1	7.6	21.5 to 25.4
Scenario 2	3.2	9.4 to 11.3
Scenario 10	1.9	10.0 to 11.6
Scenario 12	15.6	36.7 to 45.2

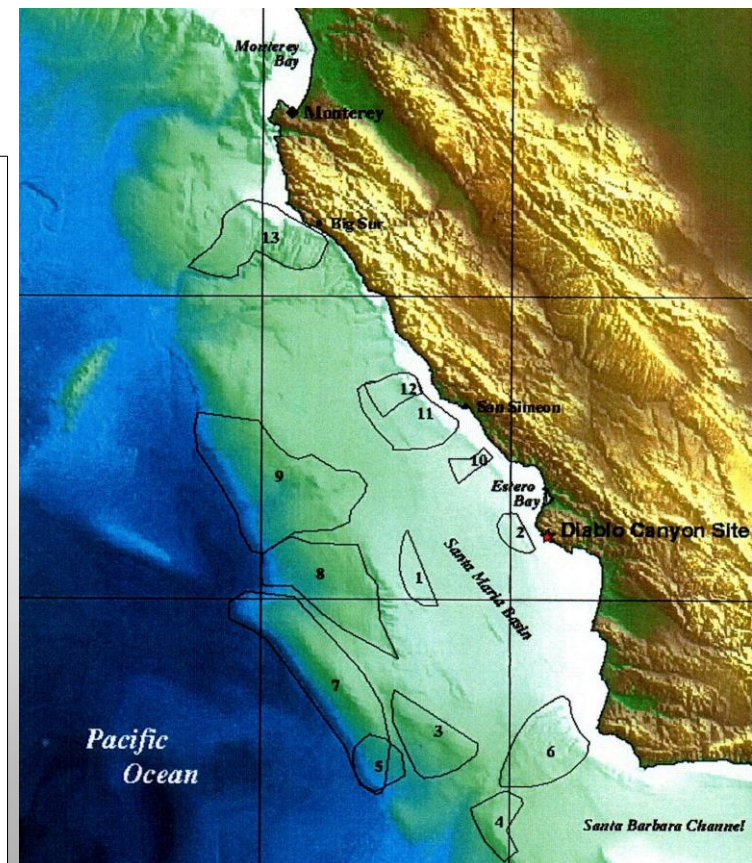
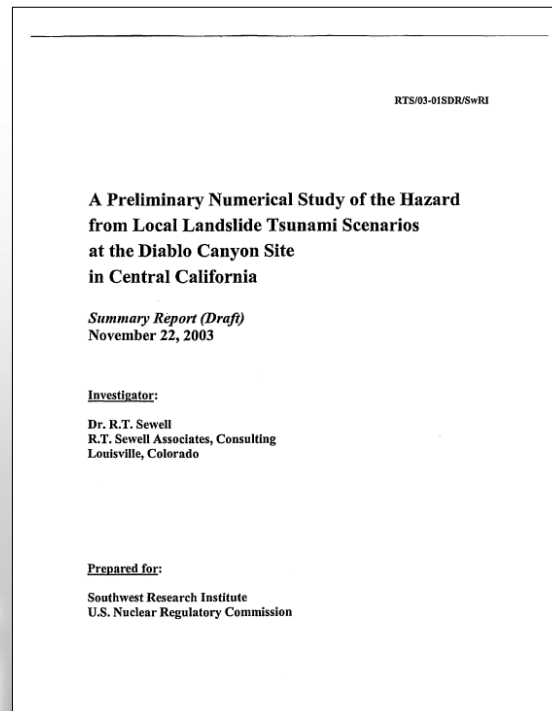


Although this is an “after the fact” comparison, Sewell performed various “sanity checks” (during the 2003 study) that parameters and results were within the range of physical observation or inference from the literature. Note that significant error bounds always apply to (and should be understood to exist for) estimated parametric relationships (such as the plot above), even if not yet quantified or illustrated.

Sewell (2003) Report

Sewell (2002-2003) Work with Southwest Research Institute (SwRI) on DCPD ISFSI SER for Tsunamis

- Sewell's (2002-2003) NRC-funded work with Southwest Research Institute (SwRI) – on review of the DCPD ISFSI safety analysis report (SAR) for tsunamis – led to preparation of the Sewell (2003) report and the analyses therein.
 - Conducted while Sewell was an independent nuclear safety consultant working with SwRI; not with Structural Integrity at the time.



Sewell (2003): What the Report Was and What it Wasn't

- It was, and continues to be:
 - A preliminary draft conveying valid and sufficient basis for discussion and motivation toward suitably improving the tsunami design basis assessment for the DCPD site (including, but not limited to, the treatment of submarine landslides), involving a suitable representation of the ITC
 - A credible work / contribution (in terms of hypothesized potential scenarios and effects – some of which are expected to be ruled in, and similarly, others that may be ruled out by the relevant ITC) that substantiates and conveys valid and useful recommendations
 - An intended helpful basis for better understanding DCPD tsunami hazard and risk

Sewell (2003): What the Report Was and What it Wasn't

- It was not, and continues to not be:
 - Itself, the full and robust, state-of-the-art study of tsunami hazard by the ITC – which it was rather intended to motivate
 - A sufficient or complete basis for characterizing DCPD tsunami hazard or for yet drawing conclusions about tsunami risk / safety of DCPD

Frequency of small, medium, large events and why Sewell (2003) evaluated comparatively rare events

- M5 earthquakes occur more frequently than M6 earthquakes, and in turn, M6 earthquakes more frequently than M7 events, etc.; yet, M5, M6, M7, etc., events (as can be justified in seismic source models) are all significant events for seismic hazard evaluation.
 - A hazard study does not focus just on relatively small (e.g., M5) events.
- Similarly, for tsunamis, Sewell (2003) did not focus on just small, medium or large SMFs, but a (fairly uniform) range of significant events, from small, moderate, large up to SMF volumes that Sewell judged to be close to a regional physical maximum, SMF Vol_{max}.
- **Note: Sewell (2003) did not make (nor claim to make) a definitive assessment of SMF volume occurrence frequencies, as doing so requires the more extensive evaluation, resources and ITC involvement that Sewell was in fact recommending.**

Expected reaction and use of the Sewell (2003) preliminary draft versus what actually happened

- Sewell expected that NRC would have questions on the study, and would hold a meeting with Sewell to discuss in detail the approach, implications and recommendations of the study, as well as a resolution plan.
 - Sewell expected the resolution plan to include finalizing the report; holding further discussions; and presenting the findings to PG&E.
 - Sewell also expected a broader involvement / interface with NRC to discuss and pursue follow-up on the other study recommendations
 - Formalization of tsunami hazard analysis methodology and implementation of multi-expert hazard studies (according to a SSHAC or modified-SSHAC approach).

Expected reaction and use of the Sewell (2003) preliminary draft versus what actually happened

- In contrast to expectations, there was no follow-up even on Sewell's first recommendation to have a meeting to discuss the report together, and Sewell had no direct feedback or visibility as to NRC's use or disposition of the report.

Key points from Sewell (2003) preliminary draft report

- In considering the Sewell (2003) report in 2016, Sewell believes the report and study remain clear and suitable for the intended objectives of presenting a credible basis for following up on the principal study recommendations and key points – and that the validity of the recommendations (i.e., need to address them) and the supporting key points in the text largely persist.

What Sewell would (perhaps) do differently today

- Programmatic:
 - Seek to facilitate a strengthened program, if possible: More clearly (and earlier) communicate the importance and implications of the work, and indicate it to be only an ***initial phase*** of what should be followed-up with a larger multi-phase, state-of-the-art effort; also, seek to strengthen stakeholder engagement, suitable funding, and facilitation of broader collaboration, where possible.
 - **Requires stakeholder cooperation**

What Sewell would (perhaps) do differently today

- Technical (for what was intended as an *initial phase*):
 - Update to use of more advanced (now-available) and diverse numerical modeling codes (for generation, propagation and run-up); if possible, apply additional code(s); quantify estimates of aleatory error in models, as possible.
 - Fine-tune scenarios, as may be possible / credible, based on new information and additional discussions with marine geologists.
 - Assess and apply a broader range of headwall scarp configurations, and evaluate related sensitivities.
 - The headscarps developed for the Sewell (2003) SMF scenarios were within a credible range, but owing to the limited number of scenarios that could be analyzed, they emphasized configurations comparable to significant observed headscarps.

Recent PG&E Studies

Sewell's Assessment of PTHA study; PG&E 2015 study / FHR work

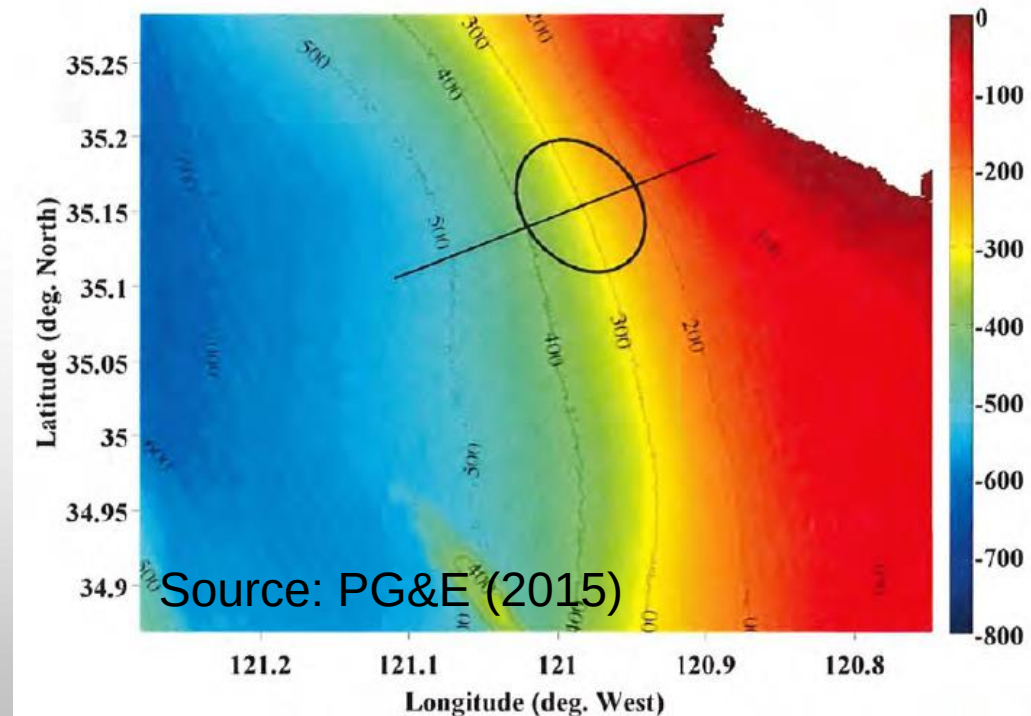
- Analyses of Goleta and Big Sur proxies by PG&E 2015 serve as interesting and useful points of reference that further illustrate the potential for application of numerical modeling to tsunami hazard assessment for DCPD
 - Performed by a highly qualified tsunami modeler
 - Employed a well-acknowledged wave modeling code
 - Further demonstrated the insights of tsunami model animations, particularly in near-site evaluations

Sewell's Assessment of PTHA study; PG&E 2015 study / FHR work

- While illustrative and useful, the analyses do not well reflect state-of-the-art for tsunami hazard study for safety analysis
 - Not convincing or justified as a conservative basis (e.g., “deterministic maximum credible event” [D-MCE*]) for landslide tsunami scenarios for DCPP
 - The size of the Goleta proxy slide (which controls over the Big Sur proxy) is rather minuscule in comparison to a largest physically realizable SMF
 - The headscarp geometries and other parameters for the proxies do not appear to be conservatively chosen (e.g., at a level defining a D-MCE)
 - Likelihoods (and their uncertainties) for the proxy scenarios are not estimated

Sewell's Assessment of PTHA study; PG&E 2015 study / FHR work

- The scenarios lack confirmation by the ITC
- The extent to which the scenarios are physically realizable and consistent with assessed / hypothesized SMF sources is not adequately elucidated
 - Goleta proxy SMF is highly artificial, idealized.
 - Location of the Goleta proxy is not well correlated with occurrence of past sliding



Sewell's Assessment of PTHA study; PG&E 2015 study / FHR work

- Whereas nuclear plant design bases should be established based on very remote annual probabilities, the maximum wave heights developed by PG&E 2015 for the Goleta Proxy (i.e., controlling event) scenario analyses are apparently only at levels comparable to those shown in local inundation maps (which conventionally, and in accordance with policy, are keyed [whether explicitly or implicitly] to higher probability events)
 - There is an apparent need to involve the experts within the ITC who perform analyses for the local tsunami inundation maps, and potentially others (those producing tsunami hazard results for State and local programs/policy, etc.), in order to help ascertain whether the scenarios modeled by PG&E 2015 are applicable to the very low annual probabilities associated with nuclear plant design and risk, or may be more applicable to higher annual probability events.

Sewell's Assessment of PTHA study; PG&E 2015 study / FHR work; etc.

- PG&E's PTHA (PEER Study of 2010) is a valuable work, but:
 - Considers only a limited hypothesis (relative to the broader credible array) of SMF source zones that is restrictive (relative to existing slide features and what is physically realizable) as to possible SMF sizes and potencies
 - Does not address the ITC and associated uncertainties needed for obtaining the CBR of the hazard.

Some Relevant Fallacies

Some Fallacies

- Fallacy 1: Sewell believes, or believed, that DCPD is unsafe for tsunamis
 - Sewell's concerns have always been about having a proper safety evaluation and a robust basis for suitable action and decisions for safety management, including the appropriate studies based on state-of-the-art methodology and confirmation by the ITC.
 - Sewell's 2003 study came at a time when: (a) a new state of the art and new recognitions about the general threat of tsunamis and SMFs had emerged; and (b) Sewell had been working intently with the tsunami science community and clients to help improve the state of the art in hazard assessment and implement the improvements in practice

Some Fallacies

- Fallacy 2: Establishing consistency with the Tsunami ITC can be side-stepped
 - Not properly considering the ITC and not assessing epistemic variations has generally led to, and will continue to lead to, unstable safety decisions
- Fallacy 3: Coordinating with tsunami inundation mapping programs and other programs is unimportant
 - Hierarchical consistency in safety policy applies
 - Critical facility design basis similar to conventional protection raises questions about consistency in evaluation and/or policy

Some Fallacies

- Fallacy 4: $10^{-4}/\text{yr}$ is too remote of a concern, and there is no need to consider such annual probability levels, or lower
 - Over 500 nuclear power reactor units globally; each must be held to tight safety standards
- Fallacy 5: Significant SMFs are not possible on shallow slopes
 - SMFs have occurred on slopes as slight as 1%
- Fallacy 6: Major events are not possible for our facilities or at our location of interest
 - Recall lessons from Columbia Shuttle; Fukushima; Katrina; Sandy; etc.; (situations where problems were foreseen before the event)

Some Fallacies

- Fallacy 7: Strike slip faulting is ineffective as a SMF tsunami generator
 - Some of the largest historically observed SMFs and landslide tsunamis are verified as being triggered by earthquakes (of faulting style that is not subduction), and the largest paleo slides are believed to be triggered by earthquakes that were not subduction events.
 - Recent publications on the Haiti earthquake and tsunami not only state the relation of strike-slip faulting and tsunami generation for that event, but discuss the implications for strike-slip-triggered SMFs offshore California.

Some Fallacies

- Fallacy 8: It is clearly known that there is a sharp transition in SMF-generated tsunami hazard at Mendocino Triple Junction (MTJ), with the landslide tsunami threat diminishing markedly for latitudes below MTJ
- Fallacy 9: We know that offshore Central California is more stable compared to other coastlines that have experienced large SMFs and/or we know that only comparatively small SMFs can occur offshore Central California within annual probability levels of interest.

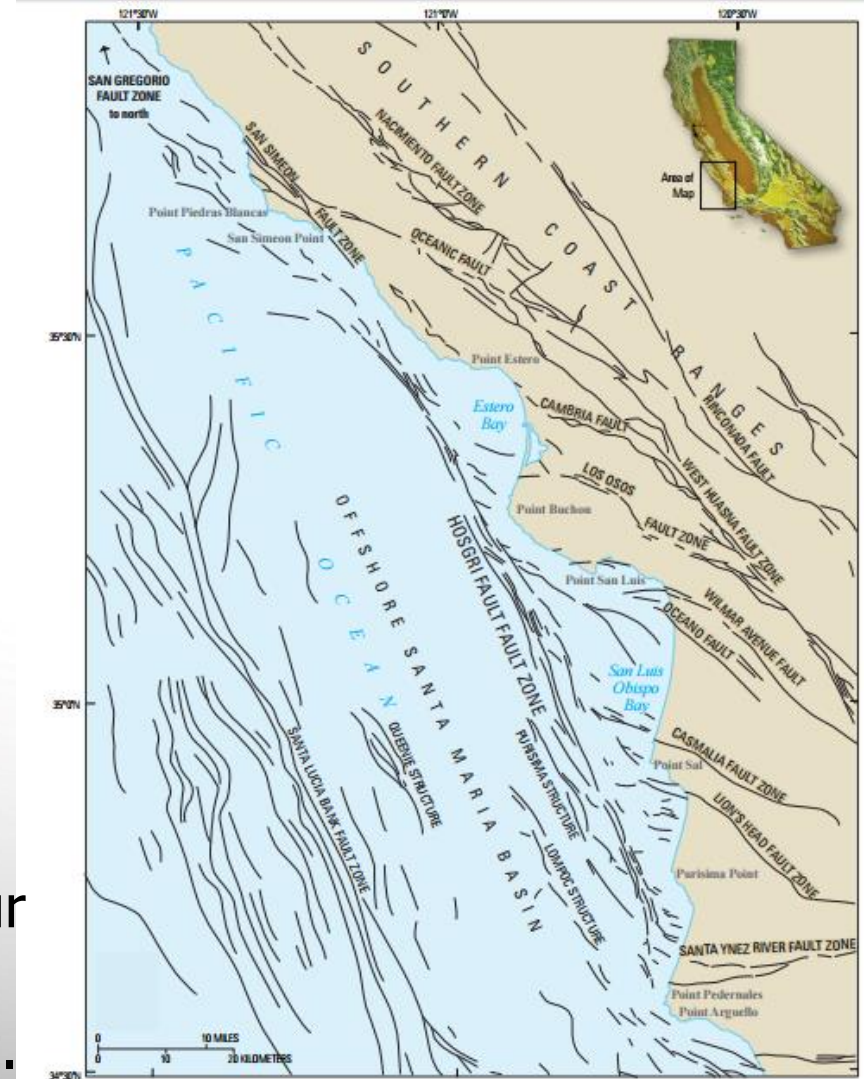
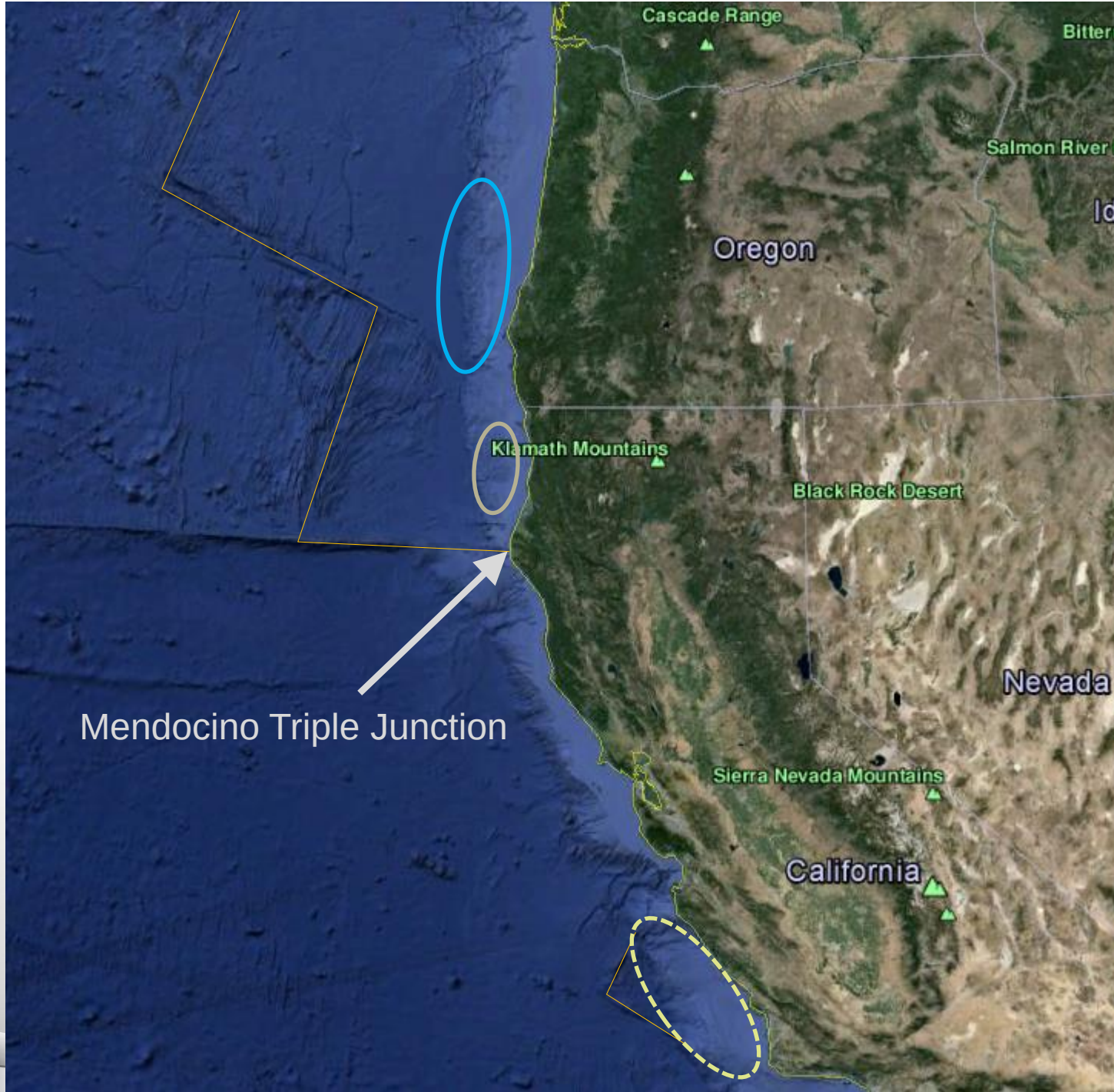
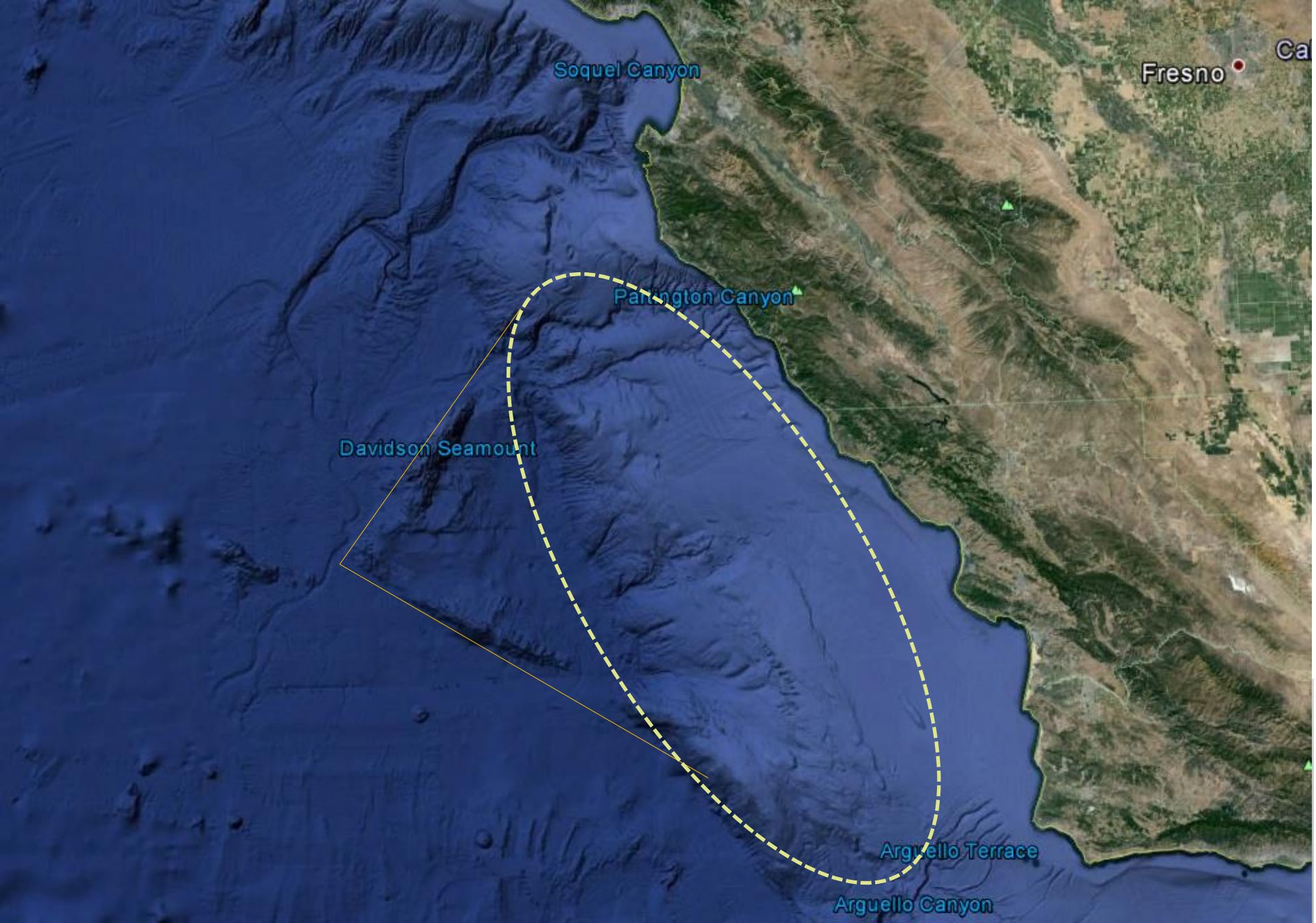


Figure 1. Fault traces in the offshore Santa Maria Basin and adjacent coastal California. The Hosgri Fault Zone forms the eastern boundary of the offshore Santa Maria Basin; the northern part is aligned with the strike-slip San Simeon/Sur/San Gregorio Fault System to the northwest (Lettis and others, 2004). The Hosgri Fault Zone is subparallel to the north-northwest trend of faults in the offshore Santa Maria Basin. However, the west-northwest trends of faults to the east of the Hosgri Fault Zone are abruptly terminated at the fault zone.





Some Fallacies

- Fallacy 10: Implications of Bartlett and other data are clear at this time and constrain the landslide tsunami hazard to a low level
- Fallacy 11: When formulating and evaluating hypotheses as to SMF source potential, paleo-data and sedimentation rates provide a more valid and sufficient basis for assessment of the hazard from future tsunamis, versus understanding the underlying geotechnical properties (i.e., engineering mechanics properties of soil and rock) and considering slope stability analyses

Some Fallacies

- Fallacy 12: Regardless of the hazard, the risk at DCPD from tsunamis less than 85 ft is now known to be clearly negligible
 - 85 ft level of DCPD power block does provide good siting-based protection
 - However, induced failures, random failures on demand (in relation to safety relevant SSCs), access/response problems and operator errors are yet possible for tsunamis lower than the power block
 - CCDPs for various cases are non-zero, can be determined, and should be included (for all tsunami levels) as part of a complete tsunami risk (PRA) study
 - For a nominal 85-ft tsunami wave, occurrence of significant wave and debris splash-up and spray (i.e., real physical phenomena not included in nominal amplitude assessments) can be expected to occur. Although the splash-up does not carry the same impact and flooding potential of the full-momentum in the nominal wave level, local adverse impact effects and flooding are still possible

Some Fallacies

- Fallacy 13: We have clear understanding as to the possible bounds (upper limits) of tsunamis and the range of tsunami characteristics that need to be considered
 - Upper bounds are established based on physical maximums (e.g., now well-established studies examine maximum ground motion from earthquakes, as well as maximum magnitudes), which are often poorly understood
 - For a hazard study to be complete (particularly for critical facilities), and most useful for PRA, it must assess hazard and its uncertainty to about 10-7/yr mean annual probability levels, explicitly and quantitatively explaining physical possibilities and likelihoods even to very extreme levels

Recommendations and Discussion

Main Theme

- Implement tsunami hazard, risk assessment methods established as suitably robust for use in decision making (>SSHAC Level 2, for critical facilities)
 - Consult the multiple relevant disciplines
 - Identify and involve members of the Tsunami ITC, and suitably train them to overcome inexperience in:
 - Quantifying hazard to extremely low annual probabilities (10^{-6} /yr mean; 10^{-7} /yr median) relevant to decision making for critical facilities
 - Explicitly quantifying aleatory variations (random error) in their models
 - Explicitly quantifying epistemic variations (knowledge variations in the face of imperfect data) and associated uncertainties
 - Moderating proponent biases through well-structured elicitation and evaluation of all credible, competing hypotheses
 - Related Notes:
 - Technical debate has limited utility outside the preceding context
 - This theme was initiated and reinforced in Sewell (2003)

Appendix: Back-Up Slides (Original Slide Report)

Contents

- Introduction
- Perspective On:
 - Pre-2003 Background
 - 2003 Event and Insights
 - 2004 Event
 - Post-2004 Developments
 - 2011 Events
 - State of the Art
 - Fallacies and Evaluation Gaps
- 2016 Insights and Updated Conclusions

Introduction: Theme and Coverage

- High-Level Theme:

- ⌈ Implement tsunami hazard, risk assessment methods established as suitably robust for use in decision making for critical facilities

- Consult the multiple relevant disciplines

- Identify and involve members of the tsunami Informed Technical Community (ITC), and suitably train them to overcome inexperience in:

- Quantifying hazard to the extremely low annual probabilities (10^{-6} /yr mean; 10^{-7} /yr median) relevant to decision making for critical facilities

- Explicitly quantifying aleatory variations (random error) in their models

- Explicitly quantifying epistemic variations (knowledge variations in the face of imperfect data) and associated uncertainties

- Moderating proponent biases through well-structured elicitation and evaluation of all credible, competing hypotheses

- ❖ Technical debate has limited utility outside the preceding context

- ❖ This theme was initiated and reinforced in Sewell (2003)

Introduction: Theme and Coverage

- Coverage:
 - Timeline of Some Key Developments
 - Background Influencing the Sewell (2003) study
 - Updated View on Sewell (2003)
 - Opinion on Progress / Advancements Since 2003
 - Specific high-level comments on PG&E's 2015 submittal
 - State of the Art, Fallacies and Evaluation Gaps
 - Suggested Future Steps

Pre-2003 Background

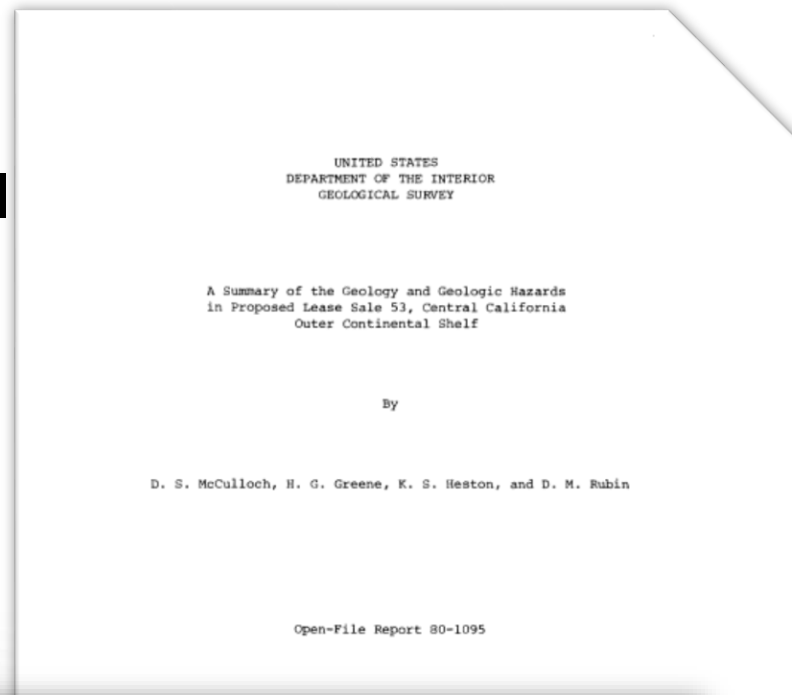
Topics

- USGS Open-File Report on USNS Bartlett Cruise Data
- Charleston Earthquake Issue and USGS Letter to NRC
- Developments Toward Robust Seismic Hazard and Risk Assessment
- 1998 Papua New Guinea Earthquake and Landslide Tsunami
- Exposition of Probabilistic Tsunami Hazard Assessment (PTHA), Tsunami Probabilistic Risk Assessment (PRA) and Related Uncertainty Assessment to the Tsunami Science Community
- Critical Value of PRA: Some Illustrations

USGS Open-File 80-1095 Report Including Bartlett Data

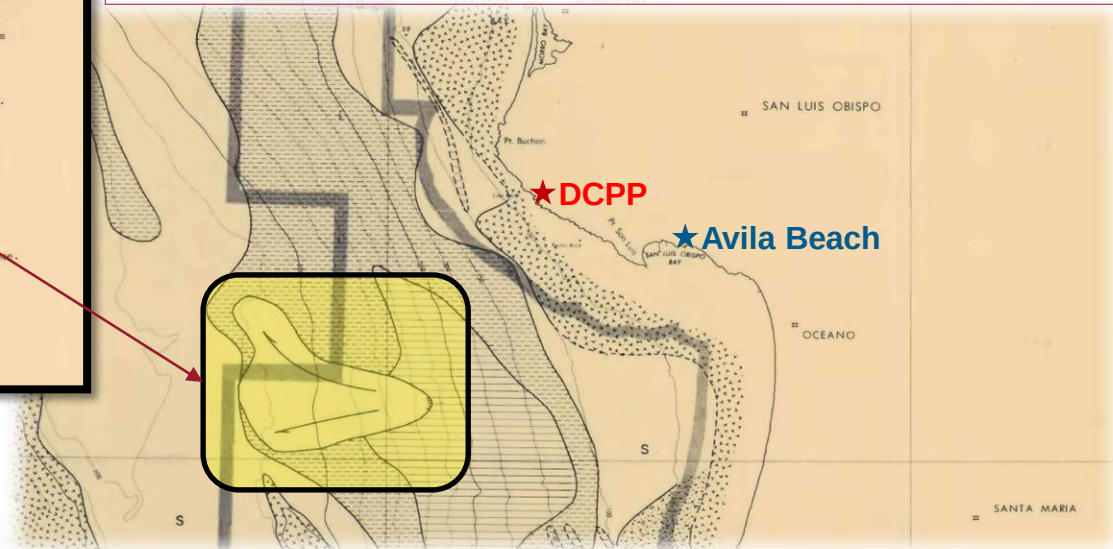
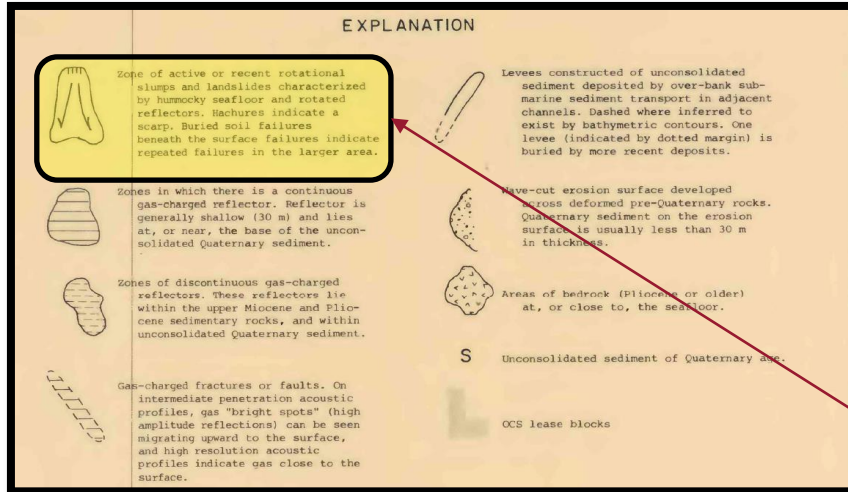
“The 1972 USNS Bartlett cruise (Greene and others, 1975) was part of a reconnaissance exploration of the central and southern California continental shelf using a deep penetration 160 Kilojoules (kJ) sparker system and satellite controlled navigation.”

- Complete set of Bartlett cruise data was not reported by USGS (1980); most data are not generally available.
- Unique and valuable data set that yet remains in 2016 to be fully considered by the Tsunami ITC.



USGS Open-File Report; Bartlett Data

"In this seismically active area earthquake induced ground motion remains the likely candidate to supply the initial energy necessary for failure."



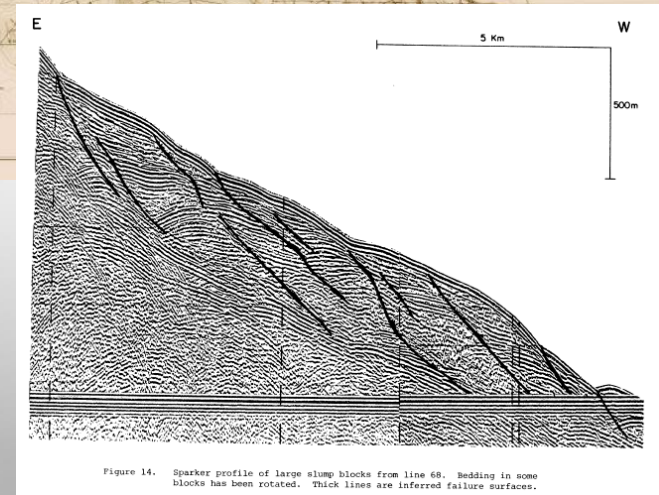
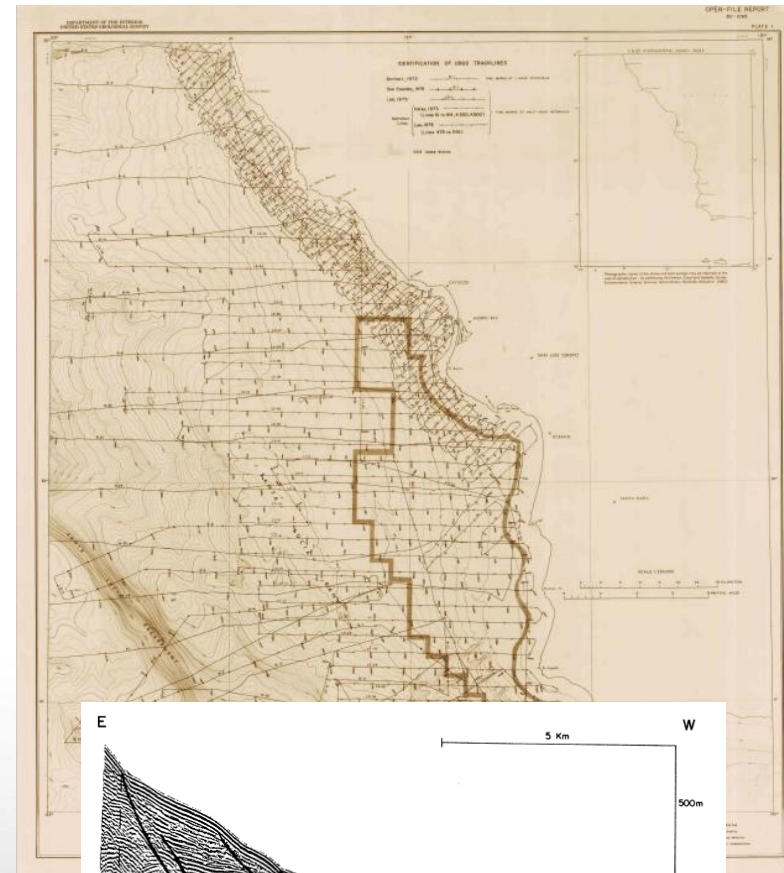
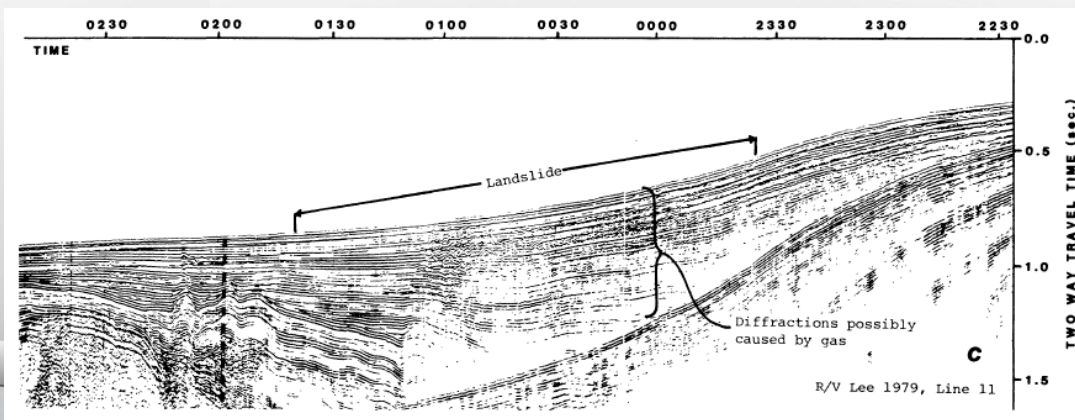
Revealed past slides, including a geologically "recent"* "large" slide (125 km²), believed to be progressive, in offshore Santa Maria Basin

- "The slope of the failure zone or surface is about 1.2°. Slumps and slides occur on similar gentle slopes in Eel River Basin, ..."
- "The cause of the slide in the offshore Santa Maria Basin is not known. No samples of the slide material have been collected, thus the mechanical properties of the sediment are not known."
- Creates a favorable structure for slide activation by seismic and/or gas hydrate initiator

*Note: "... sliding was sufficiently recent that sedimentation and/or erosion has not had time to mask the slide topography" ... which can be interpreted as likely order [~O(•)] of 100's to perhaps even some few 1000's years recent; or possibly, progressively active through that time, at low dynamics, up to and including current time.

USGS Open-File Report; Bartlett Data

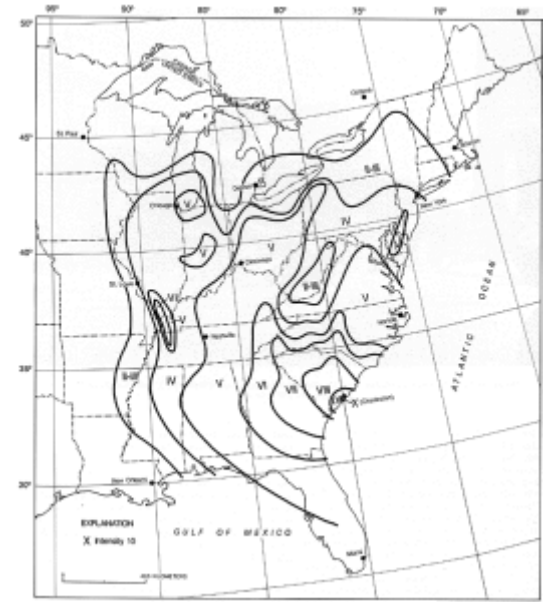
- Little Discussion on Relationship of Submarine Slides to Tsunami Hazard
- Only a Small Portion of Bartlett Data Was Reported; Focus on Offshore Santa Maria Basin
- Implications to the Steeper Continental Slope Not Well Exposed
- Major Message Is that Significant Slides (Even Within Gentle Sloping Shelf Areas) Occur Offshore Central California
- Deeper Disturbances Are Found Along Some Areas of the Slope



Charleston Earthquake Issue and USGS letter to NRC

- USGS (1982) to NRC:

“Because the **geologic and tectonic features of the Charleston region are similar to those in other regions of the eastern seaboard**, we conclude that although there is no recent or historical evidence that other regions have experienced strong earthquakes, the historical **record is not, of itself, sufficient ground for ruling out the occurrence in these regions of strong seismic ground motions similar to those experienced near Charleston in 1886**. Although the probability of strong ground motions due to an earthquake in any given year at a particular location in the eastern seaboard may be very low, deterministic and **probabilistic evaluations of the seismic hazard should be made for individual sites in the eastern seaboard to establish the seismic engineering parameters for critical facilities.**”



1886 Charleston Earthquake



Charleston Earthquake Issue

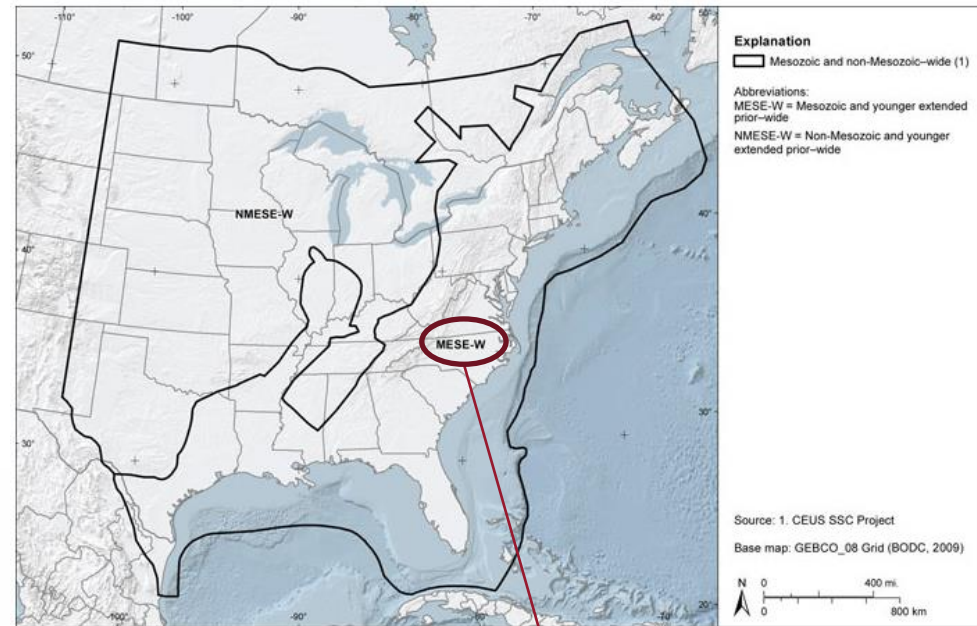
- “Charleston Earthquake Issue”:
[EPRI NP-6395-D by McGuire et al. (1989); EPRI TR-103126 by Sewell et al. (1993)]
 - Explicit recognition that **large earthquakes of 1886 Charleston Earthquake size ($\sim M 6.5$) and larger have some small probability of occurring where favorable geologic conditions may exist**
 - **Probabilistic seismic hazard methodology (PSHA) is appropriate** to quantify the associated ground-motion hazard and its uncertainty
- EPRI and LLNL PSHA studies – involving several experts from multiple disciplines, addressing competing hypotheses and uncertainties – were undertaken in the 1980’s, with both studies reporting results in 1989
- Planning of subsequent seismic margin and probabilistic risk assessment (PRA) studies – for the Independent Plant Evaluation of External Events (IPEEE) program – was based on results of the EPRI and LLNL PSHA studies.

Charleston Earthquake Issue

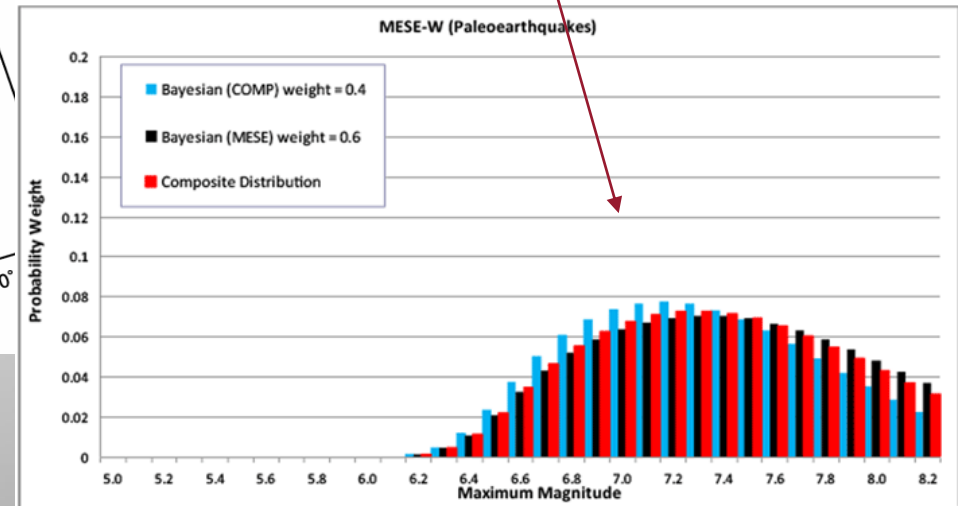
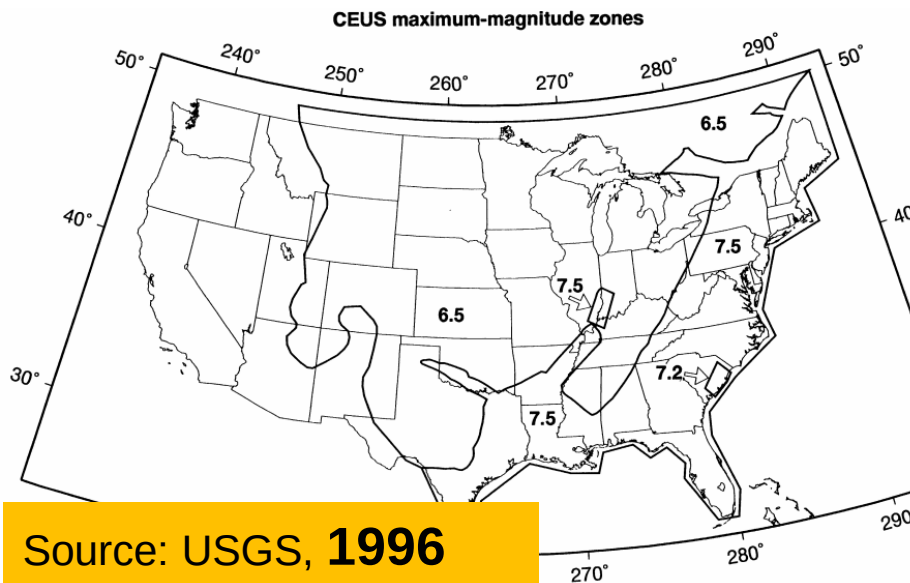
- A new state of the art in hazard and uncertainty assessment for critical facilities began to emerge from the EPRI and LLNL PSHA studies:
 - Multiple experts proposing and addressing the possible array of credible competing hypotheses held within the expert community
 - Large events must be considered with suitable likelihood/weights where they cannot be systematically and conclusively ruled out by the expert community
 - Now, assessments/hypothesis of maximum magnitude (M Max) values for the central and eastern US (CEUS) range from about M 5.4 to M 8.2, depending on the specific region under consideration
 - Focus is on assessing not just central estimates of hazard, but the full uncertainty distribution of the hazard – the center, body and range (CBR)
 - Results of hazard analysis are compatible with probabilistic risk assessment (PRA)
- **Implications to Tsunami Hazard Assessment:**
 - **Multi-expert, multi-disciplinary effort that must represent the expert community**
 - **Large source events considered where they can't be conclusively ruled out by the ITC**
 - **Aim must be to develop the entire uncertainty distribution (i.e., CBR of hazard)**
 - **Although tsunami hazard community is about 30 years behind the development of the seismic hazard community, lessons from PSHA can greatly accelerate needed progress in tsunami hazard assessment for critical facilities**

Charleston Earthquake Issue

- Trend over time has gone to increased recognition among the ITC of larger Mmax values (often, also larger hazard).
- Prior Mmax distributions, which are based on global Mmax data, are generally evaluated and given some weight.
- **Analogous to appropriate treatment of maximum parameters (e.g., maximum SMF volumes) in PTHA.**



Source: CEUS Model, **2015**; EPRI 3002005684



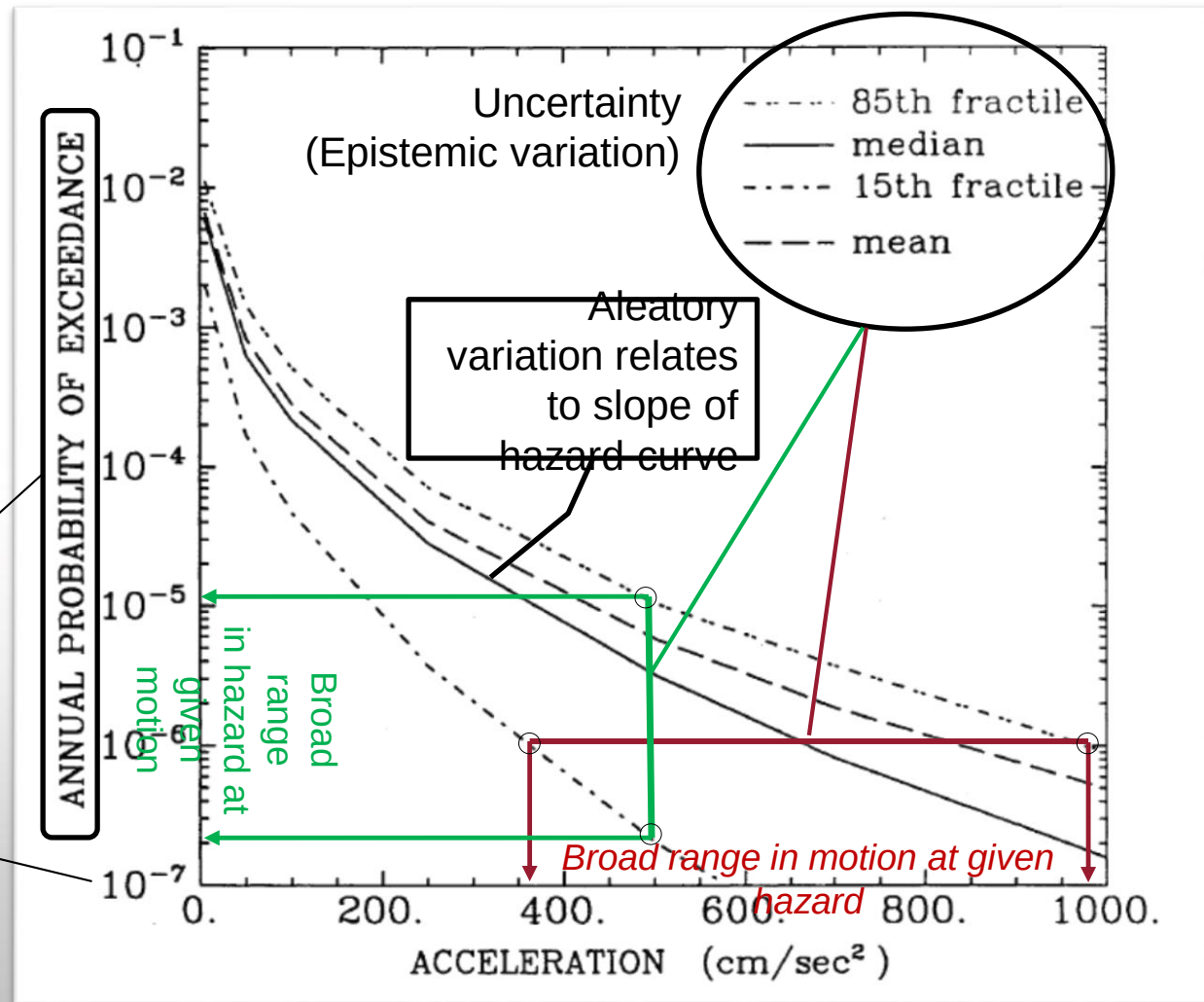
Charleston Earthquake Issue

- Example Site-Specific PSHA Result from EPRI Study (1989)

- Hazard curves are “tails” of a complementary cumulative probability distribution
- **Tsunami hazard results can be similarly conveyed**

Hazard measured as annual exceedance probability

Hazard curves extend to $10^{-7}/\text{yr}$



Source: EPRI NP-6395-D (1989)

Further Developments Toward Robust Seismic Hazard and Risk Assessment

- SSHAC (Senior Seismic Hazard Analysis Committee) Approach:
[NUREG/CR-6372 by Budnitz et al. (1997)]
 - Lessons / insights from EPRI, LLNL, Revised LLNL and other studies
 - Structured elicitation of experts and explicit uncertainty assessment based on CBR of the informed technical community (ITC)
 - Level 1 to 4 analysis framework that incorporates proponent views while aiming to manage/eliminate “proponent bias” and other sources of bias
 - State of the art for hazard analyses involving the earth sciences
 - Has been applied to studies of seismic hazard and volcano hazard
 - Several SSHAC studies (at Level 2 to 4) have been performed to date
 - Sewell has participated on review panels for three Level-4 studies (Yucca Mountain, Swiss PEGASOS, and Swiss PRP)
 - A SSHAC study generally produces hazard results that are fully compatible (as inputs) to probabilistic risk assessment (PRA) studies

Further Developments Toward Robust Seismic Hazard and Risk Assessment

- Advances Continue in the Application of SSHAC PSHA Studies and Seismic PRA Continue (e.g., Recent Studies for CEUS NPPs and DCP)
- Implications to Tsunami Hazard Assessment
 - “Tsunami ITC” is in a situation largely dominated by reliance on strong proponent views / biases, as was the Seismic ITC during the 1980’s.
 - To produce robust tsunami hazard estimates and their uncertainties, the Tsunami ITC of tsunami hazard assessment is in need of training and actual experience in structured elicitation and the SSHAC approach.
 - Since 1998, Sewell has worked closely with experts among the Tsunami ITC, and has evaluated the situation of inadequate uncertainty (epistemic) analysis, predominantly proponent viewpoints, and inadequate random (aleatory) error analysis in applied methods, models and data.
 - Sewell has explained and promoted to the Tsunami ITC increased understanding of the SSHAC approach, as well as methodology for probabilistic tsunami hazard assessment (PTHA) and its value for tsunami probabilistic risk analysis (PRA) of critical facilities.

1998 Papua New Guinea Earthquake and Landslide Tsunami

- “The Papua New Guinea (PNG) tsunami of July 1998 was a seminal event because it demonstrated that relatively small and relatively deepwater Submarine Mass Failures (SMFs) can cause devastating local tsunamis that strike without warning.”
– *Tappin, Watts and Grilli, 2008*
 - SMF was a slump having width of ~ 4.2 km, a length of ~ 4.5 km, and a thickness of ~ 750 m. The slump volume is estimated to be around 6.4 km^3 .
 - Observation suggests at least 15 m (~ 50 ft) peak run-up.
 - Model estimates of potential peak run-up are at nearly 22 m (~ 72 ft)

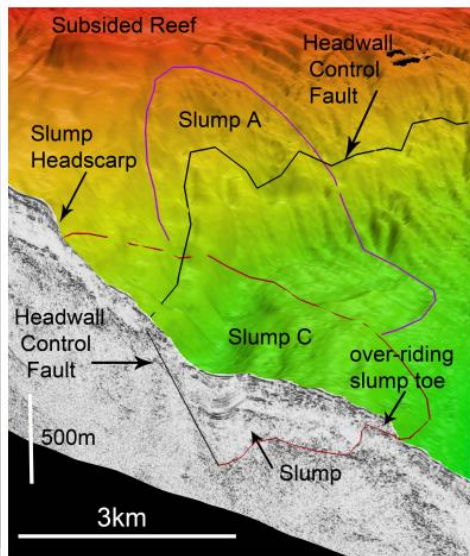


Fig. 3. 3-D image of the Amphitheatre, including seismic cutaway of slump C, viewed from the northeast. The headwall of the slump coincides with a control fault. This fault channelled artesian water pumped up from depth to the slump failure surface, triggering the slump itself around 12 min after the main shock. Vertical exaggeration 3x. See text for discussion.

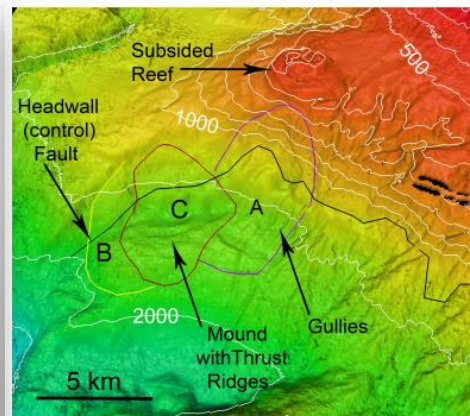
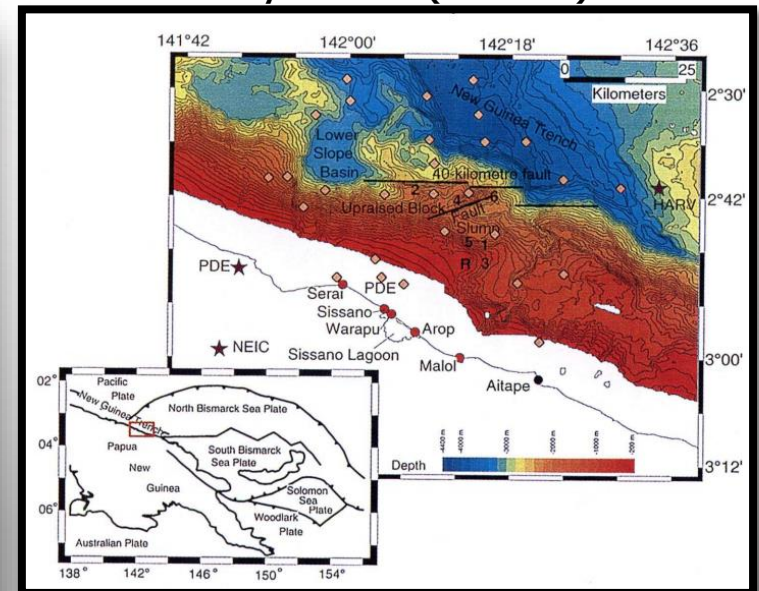


Fig. 2. 3-D image of the Amphitheatre viewed from the northwest. The three slumps (A, B and C, labelled by decreasing age) are identified together with the control fault at the base of the headscarp. Note the change in seabed morphology from the heavily gullied area in the right of the image (slump A) to that to the left (slumps B and C), where gullies are absent. Water depths are in metres. Vertical exaggeration 3x. See text for discussion.

Tappin, Watts and Grilli, 2008



Tappin, 1999.

1998 Papua New Guinea Earthquake and Landslide Tsunami

- In relation to size descriptions of submarine landslides / SMFs, note that Tappin, Watts and Grilli (2008) describe the 6.4 km³ PNG SMF as “relatively small”, whereas the recent Goleta SMF (with significant slide and tsunami generation occurring as recently as 1812) in the Santa Barbara Channels was 1.51 km³. By comparison, Sewell (2003) describes SMFs of 3.18 km³ and 1.88 km³ (Scenarios 2 and 10) as “moderately small” and a SMF of 7.56 km³ (Scenario 1) as “moderate-size”.

Although the Goleta SMF was a significant event, common descriptions suggest that it would not be generally considered by the Tsunami ITC as a “large” SMF – e.g., relative to the size of other past SMFs.

Some past single-event SMFs are known to be as large as many 1000's of km³, and past event complexes have size up to about 20,000 km³ [Agulhas Slide, SE Africa; age Pliocene to 2500 ya; as reported by Dingle (1977), and cited by Uenzelmann-Neben and Huhn (2009) and others.]

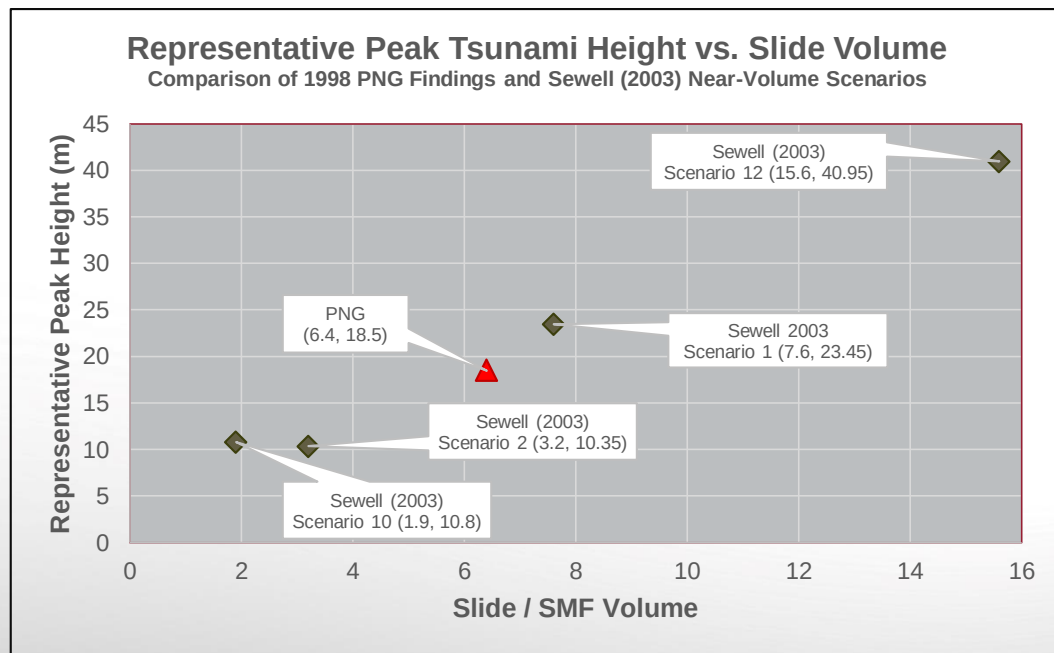
1998 Papua New Guinea Earthquake and Landslide Tsunami

- The PNG tsunami was also pivotal within the Tsunami ITC because it was controversial and eventually drew much greater attention to SMFs / submarine landslides as an important tsunami generating mechanism, and the possibility to numerically model such scenarios
 - For strike-slip faulting, similar insights were revealed from the 2010 event in Haiti
- In light of occurrence and subsequent scientific study of the PNG tsunami – which is an event resulting in significant empirical data collection and application / testing / advancement of modeling tools – the implications became clear as to validity of this type of scenario and the need to study the potential and effects of SMF scenarios, up to the maximum scenarios supported by geological conditions, at other coastal locations
- The PNG event occurred just before Sewell started working closely with the Tsunami ITC and, with Dr. Charles L. Mader (LANL; Mader Consulting), in performing a detailed tsunami hazard study for a LNG plant in West Papua

1998 Papua New Guinea Earthquake and Landslide Tsunami

- In relation to SMF scenario development in Sewell (2003): the following comparison (albeit simplified) – of peak-wave run-ups from 1998 PNG and reported peak wave amplitudes [Table 2; Sewell (2003)] at the DCPD site – is made:

Scenario	Volume (km ³)	Peak Wave Amplitude (m)
1998 PNG	6.4	15 to 22
Scenario 1	7.6	21.5 to 25.4
Scenario 2	3.2	9.4 to 11.3
Scenario 10	1.9	10.0 to 11.6
Scenario 12	15.6	36.7 to 45.2



Although this is an “after the fact” comparison, Sewell performed various “sanity checks” (during the 2003 study) that parameters and results were within the range of physical observation or inference from the literature. Note that significant error bounds always apply to (and should be understood to exist for) estimated parametric relationships (such as the plot above), even if not yet quantified or illustrated.

Exposition of PTHA, Tsunami PRA and Related Uncertainty Assessment to the Tsunami ITC

- During 1998-1999, Sewell worked with Mader on tsunami scenario-based hazard assessment (numerical model study) for the Tangguh LNG development in West Papua (details are proprietary and documented in consulting reports.)



Exposition of PTHA, Tsunami PRA and Related Uncertainty Assessment to the Tsunami ITC

- Sewell extended the initial Tangguh tsunami scenario study to incorporate estimates of scenario likelihoods based on the well-established, robust Cornell (1968) hazard methodology.
- In a consulting report to BP-AMOCO completed about 2001 / 2002, Sewell developed and explained formulation for probabilistic tsunami hazard assessment (PTHA) based on extension of the Cornell approach to various tsunami generating mechanisms.
 - To Sewell's knowledge, this was the first development of PTHA formulation, and the Tangguh LNG project is the first case where PTHA was applied, adapting the Cornell and employing numerical modeling of tsunamis.
- Sewell's work also explained treatment of both aleatory (random) and epistemic (expert-knowledge) variations in PTHA.

Exposition of PTHA, Tsunami PRA and Related Uncertainty Assessment to the Tsunami ITC

- In May 2002, Sewell was invited by Dr. C.L. Mader and the International Tsunami Society to present on the topic of probabilistic tsunami hazard and risk assessment

Tsunami Society

Second Tsunami Symposium - Program and Abstracts

May 28- 30, 2002

East-West Center, University of Hawaii, Honolulu, Hawaii, USA

PROGRAM

<http://tsunamisociety.org/Symposium2Program.html>

VULNERABILITY - 5/30/02 Morning - G. Curtis, Chairman

8:30 - Tsunami Vulnerability in Greece- M. Papathoma, D. D-Howes, etc., UK

8:55 - Tsunami Hazards in Canada - J. Clague, T. Murty, etc, Canada

9:20 - Tsunami Hazard in Indonesian Region - J. Rym, CEBA

9:45 - Tsunamigenic Efficiency of Stratovolcanoes - G. Pararas-Carayannis, Honolulu

Break

10:30 - TOPICS and Geowave - P. Watts, etc - AEF

10:55 - Probabilistic Tsunami Hazard and Risk Assessment- R. Sewell, RTSAC

Well-established approaches for probabilistic seismic hazard analysis (PSHA) are adapted to the problem of probabilistic quantification of tsunami hazards. Whereas the PSHA approaches result in estimates of annual exceedance frequencies (or, equivalently, return periods) of earthquake ground motions, their adaptation to probabilistic tsunami hazard analysis (PTHA) result in estimates of annual exceedance frequencies (or return periods) of tsunami wave heights, run-up elevations, or other wave characteristics of scientific and engineering interest. The methodological adaptation is sufficiently general to address all tsunamigenic sources, not just earthquakes. As for PSHA, the format of PTHA results is particularly compatible for use in the development of appropriate zoning criteria and other input for codified siting and design of buildings, and has applications (among others) in design of harbor facilities, offshore structures, and other important facilities often located on coasts (e.g., nuclear power plants, natural gas plants, etc.). Logic-tree methodology, which is useful to formally account for multiple expert opinions in evaluating confidence bounds on probabilistic hazard results - and which has been successfully applied on extensive basis for conveying the scientific uncertainty in PSHA results for important projects - is also presented and adapted to probabilistic tsunami hazard evaluation. The framework for incorporating PTHA results (and related scientific uncertainties) in to overall risk assessment/management and related safety decision-making is also discussed.

Exposition of PTHA, Tsunami PRA and Related Uncertainty Assessment to the Tsunami ITC

- Since 2002, Sewell has presented and published at various meetings of the Tsunami ITC and of other earth-science groups, and initiated discussions with a number of tsunami experts (Mader, Watts, Grilli, Pararas-Carayannis, Power, Geist and others) promoting the methodology, value and advancement of:
 - PTHA and assessment of aleatory variations
 - Engineering characterization of tsunamis
 - Tsunami PRA
 - Application of the SSHAC methodology for uncertainty / epistemic assessment in representing the CBR of the ITC
- Geist and Parsons (2006; *Natural Hazards*), as well as González (2009 & 2011; *NRC/USGS Workshop on Landslide Tsunami Probability*) and others, have since taken up authorship on adaptation of the Cornell and SSHAC approaches to PTHA, although with some needed fixes, improvements and increased applicability for critical facilities.

Exposition of PTHA, Tsunami PRA and Related Uncertainty Assessment to the Tsunami ITC

- In agreement with Sewell's advice since 1998, Geist & Parsons (2006) note:
 - "Determining the likelihood of a disaster is a key component of any comprehensive hazard assessment. This is particularly true for tsunamis, even though most tsunami hazard assessments have in the past relied on scenario or deterministic type models."
 - "... methods commonly used in PSHA can be modified for use in PTHA"
- **This progress clarifies that application of Cornell-based PTHA within a SSHAC (or SSHAC-type of multi-expert) framework, for developing robust aleatory and epistemic analyses – producing results that suitably represent the CBR of the ITC – is now both an expectable and implementable state of practice for existing and future tsunami hazard studies and dependent safety evaluations (risk assessment, inundation studies, etc.)**
 - **First applied and explained over 15 years ago; reported in peer-reviewed literature over 10 years ago.**

Exposition of PTHA, Tsunami PRA and Related Uncertainty Assessment to the Tsunami ITC

- Despite this progress, the Tsunami ITC has yet low experience in application of robust hazard methods for critical facilities, and in particular, a lack of practical experience with the SSHAC approach (similar to the inexperience of the Seismic ITC in the mid-1980's).
 - The Tsunami ITC additionally has limited experience in nuclear safety / risk assessment, including the need to evaluate the CBR of tsunami hazard results for extremely low annual probabilities.
 - The Tsunami ITC is dominated by proponent views of individual experts, with limited (to no) background quantifying aleatory error in their models or in evaluating the epistemic variations / uncertainties among the ITC
- **Overcoming these issues requires suitable training, as is typically conducted with efficiency in the early stages of a SSHAC study.**

Exposition of PTHA, Tsunami PRA and Related Uncertainty Assessment to the Tsunami ITC

- The situation is somewhat ameliorated as members of the Seismic ITC – who possess greater practical experience in the Cornell hazard methodology and SSHAC approach (as applied to PSHA) – are (particularly since the 2004 Indian Ocean and 2011 Japan / Tohōku Tsunami) demonstrating increased interest and involvement in tsunami hazard studies. However, the Seismic ITC generally lacks the same depth of background and understanding of tsunami physics and behavior that is possessed by the Tsunami ITC.

Exposition of PTHA, Tsunami PRA and Related Uncertainty Assessment to the Tsunami ITC

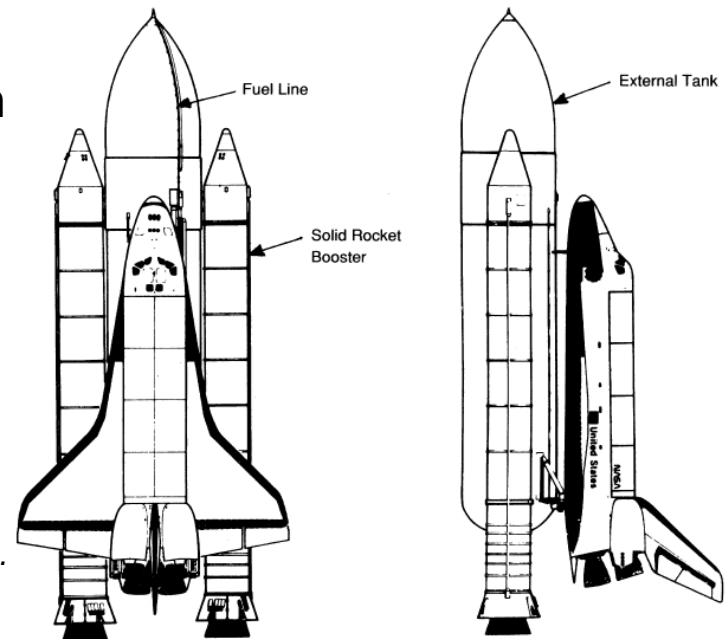
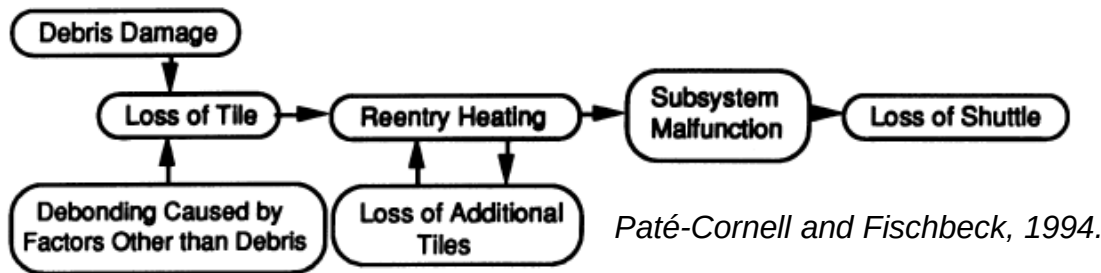
- In addition to (widely known) regional tsunami warning systems, some special-purpose local tsunami warning systems have been proposed, illustrating that employing a local warning system can be considered as a candidate risk management strategy for critical facilities and operations.
 - In 2002 work for BP, Sewell & Mader developed the conceptual design for a risk-based tsunami warning system to protect the Tangguh LNG plant and tanker loading operations against local tsunamis, including cases where short (but yet useful) warning lead time may apply.
 - Local tsunami warning system concepts have been proposed for potential risk mitigation for cruise ships near/at port.
- **More generally, tsunami probabilistic risk assessment (PRA) is an important tool for decision making concerning risk reduction and optimal risk management.**
 - **Cornell-based PTHA within a SSHAC framework is most compatible with PRA implementation.**

Critical Value of Probabilistic Risk Assessment (PRA): Some Illustrations

- Paté-Cornell and Fischbeck Reported in 1994 on Their 1990 PRA Study of Space Shuttle Tiles
- Identified Foam Debris Striking Space Shuttle Tiles as a Dominant Shuttle Risk, and Developed Specific Technical and Organizational Fixes that Were Largely Unheeded
 - 13 Years Prior to Columbia Disaster

Risk Insights Existing from 13 Years Earlier (1990 Study, Published in February 1994)

This Type of Shuttle Failure Was Specifically Called Out and Identified as Important Through Probabilistic Risk Assessment (PRA), Even Though Such Type of Shuttle Failure Had Never Before Occurred.



"We recommended that NASA inspect the bond of the most risk critical tiles and reinforce the insulation of the external systems (external tank and solid rocket boosters) that could damage the high-risk tiles if it debonds at take-off. We computed that such improvements of the maintenance procedures could reduce the probability of shuttle accident attributable to tile failure by about 70 percent." – Paté-Cornell and Fischbeck, 1994.

Risk Insights Existing from 13 Years Earlier

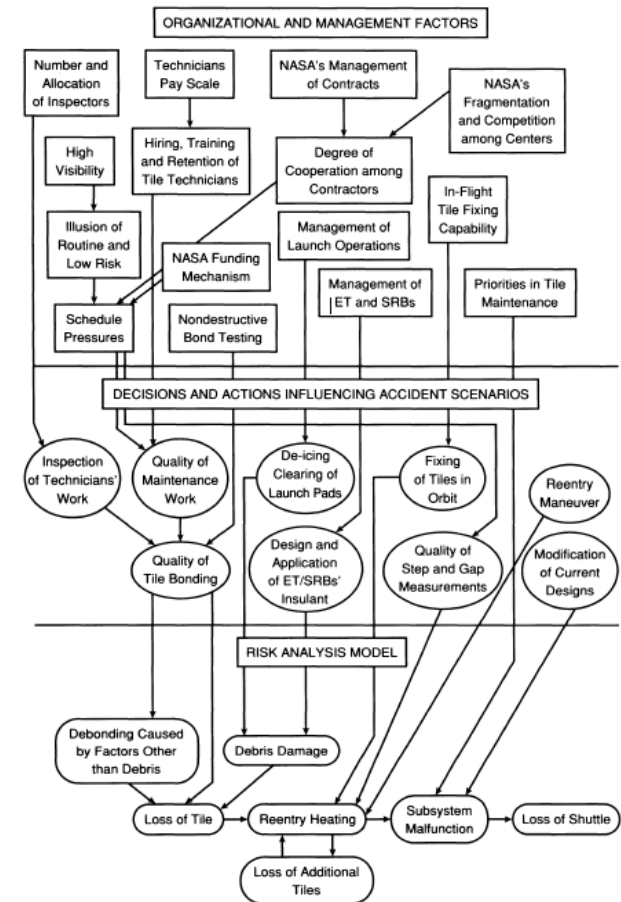
The PRA Study Identified Not Only Technical Factors, but Also Management Organization and Decision Factors

"NASA seems to have grown from a can-do organization to a large bureaucracy in which the influence of the scientists has markedly decreased ...

Soon after the shuttle's introduction, the agency shifted from a conservative attitude of 'launch if proven safe' to an attitude of 'launch unless proven unsafe.' This optimism was more common among managers than among engineers and scientists ... [Feynman 1988] ...

To some extent, these same organizational factors affected the processing of the tiles and, in particular, their maintenance between flights, which often took place under tight schedule constraints...

NASA must find new ways of being cost-effective because it simply cannot afford financially or politically to lose another orbiter.— Paté-Cornell and Fischbeck, 1994.



Paté-Cornell and Fischbeck, 1994.

2003 Event and Insights

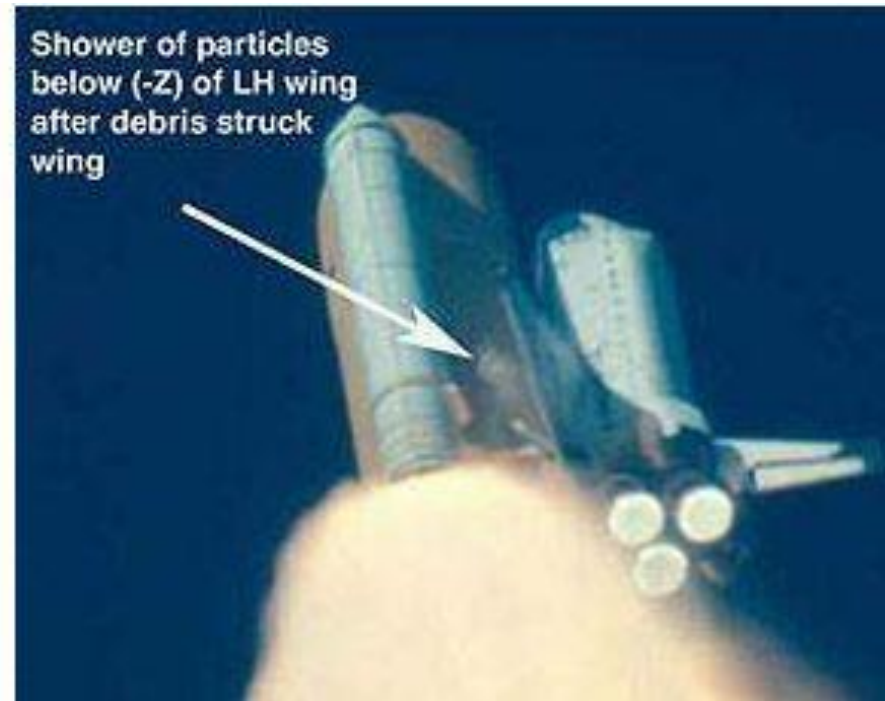
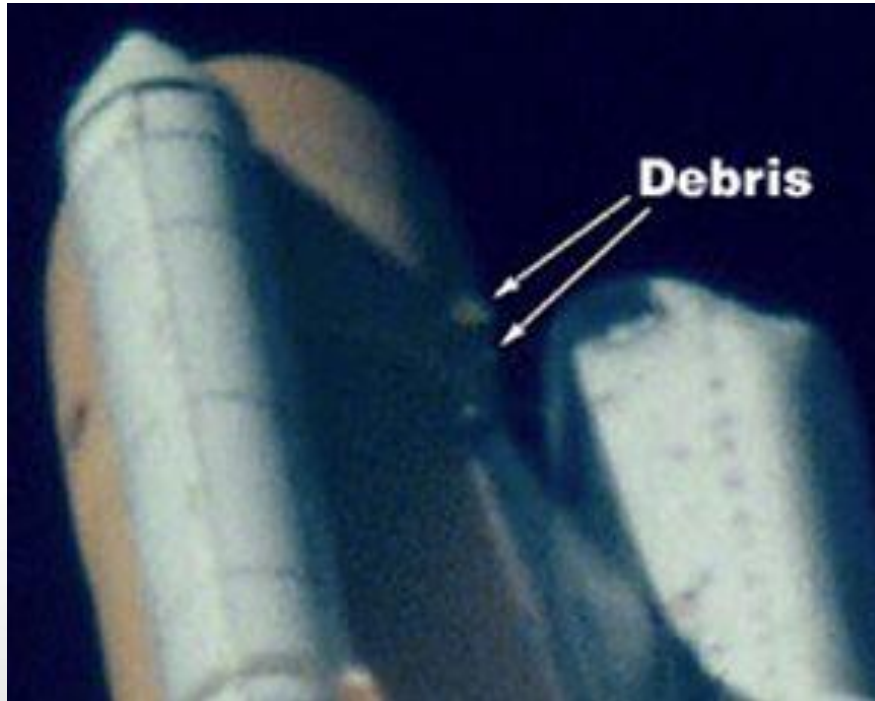
Topics

- Columbia Disaster (Feb. 2003) and Accident Investigation
 - Pate-Cornell and Fischbeck (1994) Revisited
 - Lessons Learned for Safety Management
- NSF Landslide Tsunami Workshop, University of Hawai`i at Mānoa; May 30-31, 2003
- Sewell (2002-2003) Work with Southwest Research Institute (SwRI) on DCPD ISFSI SER for Tsunamis
 - Sewell (2003): what the report is and what it isn't
 - Frequency of small, medium, large events and why Sewell (2003) evaluated comparatively rare events
 - Expected reaction and use of the Sewell (2003) preliminary draft versus what actually happened
 - Key points from Sewell (2003) preliminary draft report
 - What Sewell would do differently today, and why

- February 2003

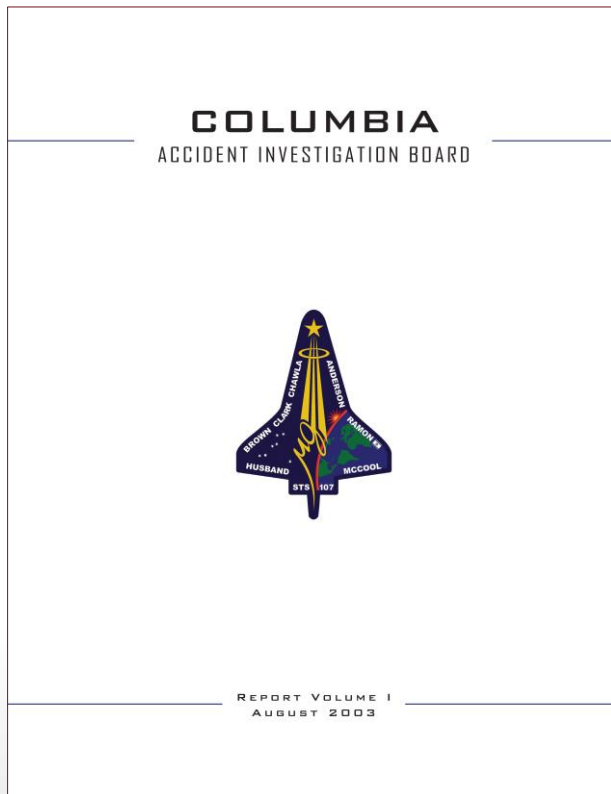


- Technical Root Cause



Columbia Accident Investigation Report, August 2003

August 2003: Columbia Accident Investigation Report



“Two years after the conclusion of that study, NASA wrote to Paté-Cornell and Fishback describing the importance of their work, and stated that it was developing a long-term effort to use probabilistic risk assessment and related disciplines to improve programmatic decisions. **Though NASA has taken some measures to invest in probabilistic risk assessment as a tool, it is the Board’s view that NASA has not fully exploited the insights that Paté-Cornell’s and Fishback’s work offered.**”

- Although the problems had been recognized in advance and the technologies, tools and solutions existed to respond, the follow-through was inadequate.
- *What similar barriers exist in applying tools for tsunami risk management?*

• Organizational Root Cause and Safety Culture Issues

“Unfortunately, NASA’s views of its safety culture ... did not reflect reality. Shuttle Program safety personnel failed to adequately assess anomalies and frequently accepted critical risks without qualitative or quantitative support, even when the tools to provide more comprehensive assessments were available.”

“The intellectual curiosity and skepticism that a solid safety culture requires was almost entirely absent. Shuttle managers did not embrace safety-conscious attitudes. Instead, their attitudes were shaped and reinforced by an organization that, in this instance, was incapable of stepping back and gauging its biases. Bureaucracy and process trumped thoroughness and reason.”

COLUMBIA
ACCIDENT INVESTIGATION BOARD



“The Shuttle Program’s complex structure erected barriers to effective communication and its safety culture no longer asks enough hard questions about risk. (Safety culture refers to an organization’s characteristics and attitudes – promoted by its leaders and internalized by its members – that serve to make safety the top priority.)”

“NASA and the Space Shuttle Program must be committed to a strong safety culture, a view that serious accidents can be prevented, a willingness to learn from mistakes, from technology, and from others, and a realistic training program that empowers employees to know when to decentralize or centralize problem-solving. The Shuttle Program cannot afford the mindset that accidents are inevitable because it may lead to unnecessarily accepting known and preventable risks.”

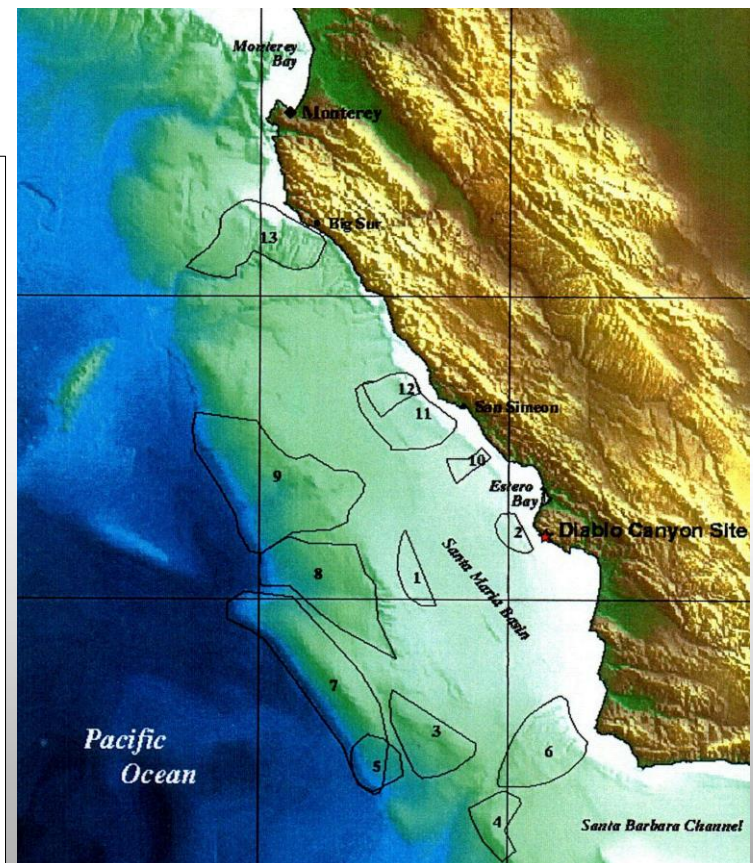
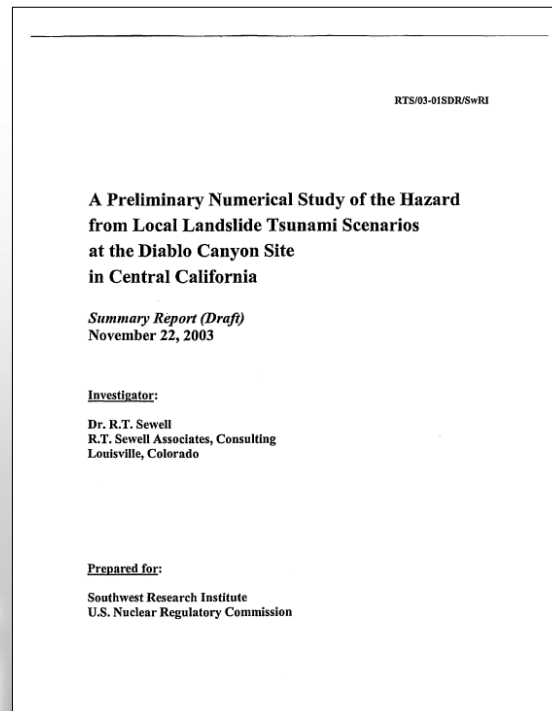
- Similar Cases Where Lessons Can Be Learned
- Other compelling cases with lessons learned for safety management and potential value of PRA
 - Hurricane Katrina, 2005 (Inundation, Extreme Wind & Waves)
 - Fukushima, 2011 (Earthquake & Tsunami [with possible SMF])
 - Hurricane Sandy, 2012 (Inundation, Extreme Wind & Waves)
- Safety management should seek valuable “take-aways” from such cases in order to help avoid future disasters
 - Avoid an attitude that similar events won’t happen in our case
 - Avoid an attitude that lessons can be realized only if the past case is exactly / highly similar to our case
 - Rather, seek reasonable insights that can be beneficial even if the case is not perfectly applicable to ours

NSF Landslide Tsunami Workshop, University of Hawaii at Manoa; May 30-31, 2003

- NSF Landslide Tsunami Workshop: “Model Benchmarking”, University of Hawai`i at Mānoa; May 30-31, 2003
 - Organized by Grilli, Kirby et al.
 - At this workshop, Sewell presented on similar topics as for the 2002 Tsunami Symposium
 - Sewell’s discussion also incorporated recommendations on landslide tsunami model benchmarking and validation to meet the particular aleatory and epistemic analysis requirements in PTHA
 - Sewell and SwRI colleagues (2015; ANS PSA-2015) more recently published on the unique considerations and aspects of methodology for tsunami model benchmarking for PTHA

Sewell (2002-2003) Work with Southwest Research Institute (SwRI) on DCPD ISFSI SER for Tsunamis

- Sewell's (2002-2003) NRC-funded work with Southwest Research Institute (SwRI) – on review of the DCPD ISFSI safety analysis report (SAR) for tsunamis – led to preparation of the Sewell (2003) report and the analyses therein.
- Conducted while Sewell was an independent nuclear safety consultant working with SwRI; not with Structural Integrity at the time.



Sewell (2003): What the Report Was and What it Wasn't

- It was, and continues to be:
 - A preliminary draft conveying valid and sufficient basis for discussion and motivation toward suitably improving the tsunami design basis assessment for the DCPD site (including, but not limited to, the treatment of submarine landslides), involving a suitable representation of the ITC
 - A credible work / contribution (in terms of hypothesized potential scenarios and effects – some of which are expected to be ruled in, and similarly, others that may be ruled out by the relevant ITC) that substantiates and conveys valid and useful recommendations
 - An intended-helpful segue for better understanding DCPD tsunami hazard and risk
- It was not, and continues to not be:
 - Itself, the comprehensive and robust, state-of-the-art study of tsunami hazard by the ITC – which it was rather intended to motivate
 - A sufficient or complete basis for characterizing DCPD tsunami hazard or for yet drawing conclusions about tsunami risk / safety of DCPD

Frequency of small, medium, large events and why Sewell (2003) evaluated comparatively rare events

- M5 earthquakes occur more frequently than M6 earthquakes, and in turn, M6 earthquakes more frequently than M7 events, etc.; yet, M5, M6, M7, etc., events (as can be justified in seismic source models) are all significant events for seismic hazard evaluation.
 - A seismic hazard study does not focus just on relatively small (M5) events, but depending on factors such as location, may examine the potential and/or effects of significant events of M5, M6, M7, etc., up to Mmax. Ultimately in a full PSHA, all potentially significant scenarios must be considered and weighted by their respective frequencies of occurrence.
- Similarly, for tsunamis, Sewell (2003) did not focus on just small, medium or large SMFs, but a range of significant events, from small, moderate, large up to SMF volumes that Sewell judged to be close to a regional physical maximum, SMF Vol_{max}.
 - **Note: Sewell (2003) did not make (nor claim to make) a definitive assessment of SMF volume occurrence frequencies, as doing so requires the more extensive evaluation, resources and ITC involvement that Sewell was in fact recommending.**

Expected reaction and use of the Sewell (2003) preliminary draft versus what actually happened

- Sewell expected that NRC would have questions on the study, and would hold a meeting with Sewell to discuss in detail the approach, implications and recommendations of the study, as well as a resolution plan.
 - Sewell expected the resolution plan to include finalizing the report; holding further internal discussions; and presenting the final study to PG&E.
 - Sewell also expected a broader involvement / interface with NRC to discuss and pursue follow-up on the other study recommendations, including formalization of tsunami hazard analysis methodology and likely implementation of multi-expert hazard studies (according to a SSHAC or modified-SSHAC approach).
- In contrast, there was no follow-up even on Sewell's first recommendation to have a meeting to discuss the report together, and Sewell had no direct feedback or visibility as to NRC's use or disposition of the report.

Key points from Sewell (2003) preliminary draft report

- In considering the Sewell (2003) report in 2016, Sewell believes the report and study remain clear and suitable for the intended objectives of presenting a credible basis for following up on the principal study recommendations and key points – and that the validity of the recommendations (i.e., need to address them) and supporting key points in the text largely persists.

What Sewell would do differently today, and why

- Programmatic:
 - Seek to facilitate a strengthened program, if possible: More clearly (and earlier) communicate the importance and implications of the work, and indicate it to be only an ***initial phase*** of what should be followed-up with a larger multi-phase, state-of-the-art effort; also, seek to strengthen stakeholder engagement, suitable funding, and facilitation of broader collaboration, where possible.
 - **Requires stakeholder cooperation**

What Sewell would do differently today, and why

- Technical (for what was intended as an *initial phase*):
 - Update to use of more advanced (now-available) and diverse numerical modeling codes (for generation, propagation and run-up); if possible, apply additional code(s); quantify estimates of aleatory error in models, as possible.
 - Fine-tune scenarios, as may be possible / credible, based on new information and additional discussions with marine geologists.
 - Assess and apply a broader range of headwall scarp configurations, and evaluate related sensitivities.
 - The headscarps developed for the Sewell (2003) SMF scenarios were within a credible range, but owing to the limited number of scenarios that could be analyzed, they emphasized configurations comparable to significant observed headscarps.
 - **Note: Sewell continued (and still continues) with relevant technical studies, including research and proposals with SwRI and NC State aimed at improvements in PTHA and Tsunami PRA, and continued (and still continues) having active involvement with the Tsunami ITC, the Seismic ITC and the risk assessment field.**

2004 Event

Topics

- 2004 Indian Ocean Tsunami
- Sewell Post-Event Reconnaissance to Thailand, Malaysia, Singapore, Australia
 - Risk-based warning system
- Sewell Presentation to Association of Engineering Geologists (AEG) Workshop at UC Davis on Hazard Assessment, Including Tsunami Hazard Assessment and Animations for Central California Submarine Landslide Tsunamis

Post-2004 Developments

Topics

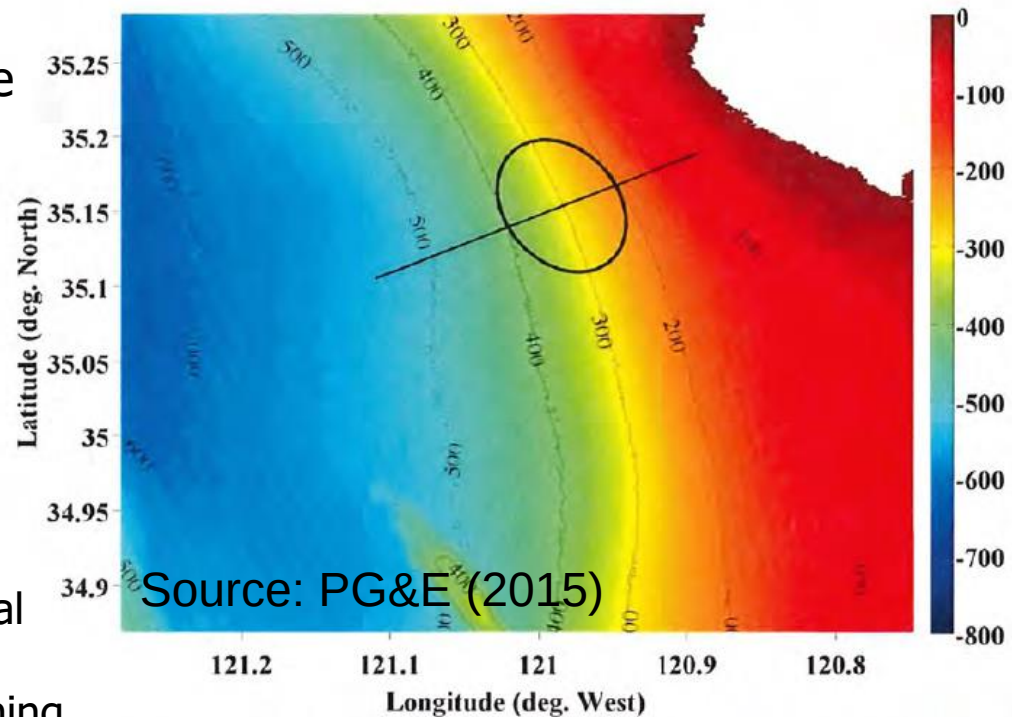
- Progress by NRC, NOAA, IAEA
- Progress by PG&E for DCPD
 - Sewell's assessment of PTHA study; PG&E 2015 study / FHR work; etc.
- Progress vis-à-vis the Earlier Recommendations of Sewell (2003)
- Related Work By Sewell
 - Tsunami science community involvement
 - Research with SwRI
 - Tsunami Society International

Sewell's Assessment of PTHA study; PG&E 2015 study / FHR work

- Analyses of Goleta and Big Sur proxies by PG&E 2015 serve as interesting and useful points of reference that further illustrate the potential for application of numerical modeling to tsunami hazard assessment for DCPD
 - Performed by a highly qualified tsunami modeler
 - Employed a well-acknowledged wave modeling code
 - Further demonstrated the insights of tsunami model animations, particularly in near-site evaluations
- While illustrative and somewhat informative, the analyses do not well reflect state-of-the-art for tsunami hazard study for safety analysis
 - Not convincing or justified as a conservative basis (e.g., “deterministic maximum credible event” [D-MCE*]) for landslide tsunami scenarios for DCPD
 - The size of the Goleta proxy slide (which controls over the Big Sur proxy) is rather minuscule in comparison to a largest physically realizable SMF
 - The headscarp geometries and other parameters for the proxies do not appear to be conservatively chosen (e.g., at a level defining a D-MCE)
 - Likelihoods (and their uncertainties) for the proxy scenarios are not estimated

Sewell's Assessment of PTHA study; PG&E 2015 study / FHR work

- The scenarios lack confirmation by the ITC as valid, suitably conservative or most relevant to DCPD tsunami hazard and design basis
- The extent to which the scenarios are physically (un)realizable and (in)consistent with assessed / hypothesized SMF sources is not adequately elucidated
 - Simple (elliptical) geometry of Goleta proxy SMF is highly idealized / artificial and does not give attention to local bathymetry and gradients in determining the shape / configuration of the likely failure surface.
 - Location of the Goleta proxy is not well correlated with occurrence of past sliding
 - Although the Goleta proxy is located somewhat near a known recent slide zone (which USGS indicates is a feature that can be mobilized / triggered by a future earthquake) as seen in Slide No. 8, the Goleta proxy apparently has much smaller areal extent (61.4 km² vs. 125 km²). The recent past slide cannot itself be designated as a D-MCE SMF size.



Sewell's Assessment of PTHA study; PG&E 2015 study / FHR work

- Whereas nuclear plant design bases should be established based on very remote annual probabilities, the maximum wave heights developed by PG&E 2015 for the Goleta Proxy (i.e., controlling event) scenario analyses are apparently only at levels comparable to those shown in local inundation maps (which conventionally, and in accordance with policy, are keyed [whether explicitly or implicitly] to higher probability events)
 - There is an apparent need to involve the experts within the ITC who perform analyses for the local tsunami inundation maps, and potentially others (those producing tsunami hazard results for State and local programs/policy, etc.), in order to help ascertain whether the scenarios modeled by PG&E 2015 are applicable to the very low annual probabilities associated with nuclear plant design and risk, or may be more applicable to higher annual probability events.

Sewell's Assessment of PTHA study; PG&E 2015 study / FHR work; etc.

- PG&E's PTHA (PEER Study of 2010) is a valuable work, but: (a) considers only a limited hypothesis (relative to the broader credible array) of SMF source zones that is restrictive (relative to existing slide features and what is physically realizable) as to possible SMF sizes and potencies; and hence, appears to represent a potentially optimistic-tending interpretation among the various possible credible hypotheses that define the uncertainty range; and (b) does not address the ITC and associated uncertainties needed for obtaining the CBR of the hazard.
 - In considering the 2010 report, Sewell believes the resulting hazard curves (e.g., for landslide tsunamis and total hazard) are apt to be found as low relative to a best estimate of the ITC. However, even if one assumes that the hazard curves represent best estimates (e.g., median values): by applying representative uncertainty bounds on the results, the mean tsunami hazard, and the hazard associated with high confidence limits, at the DCPD site would appear as being more significant than the PG&E 2010 hazard curves.

2011 Events

Topics

- Fukushima
- Space Shuttle Program (STS) Retired
- Decision in Some Countries to End of Life Their NPPs
 - Observation: Past risk studies have determined the societal risk from nuclear power to be within background levels. From the view of collective public perception / “climate” favorable for a long-term surviving and thriving industry, additional de facto criteria seem to apply. A strong future for the nuclear power industry (as a meaningful part of society’s overall energy “portfolio”) appears to depend on cost-effectively managing risk such that the frequency of a core-damage event occurring anywhere worldwide is consistently very remote – e.g., that significant core-damage events with radiological release occur less than once in a person’s typical/average lifetime (implying that the mean repeat time of a core damage event anywhere globally should be no less than about 80 years [i.e., $\sim O(100)$ years]).

State of the Art

Topics

- IAEA Guidance and El 50 m (~150 ft) Siting
- PTHA Methodology
 - Cornell-based probabilistic approach for aleatory evaluation
 - Total probability theorem, synthesizing all possible scenarios and their likelihoods
 - SSHAC (Senior Seismic Hazard Analysis Committee) approach for evaluating the center, body and range (CBR) of the informed Technical Community (ITC) based on structured Uncertainty Analysis, Logic Trees
 - SSHAC document establishes the critical importance of assessing CBR of ITC
 - Address all credible competing hypotheses

Topics

- Use and Limitations of Methods and Data
 - Tsunami modeling and animations
 - The need to explicitly measure the error (aleatory variation) in models of the ITC
 - Importance of slope stability analysis (and other justified approaches) as a competing hypothesis
 - Paleo data; and uncertainties in adjustment and interpretation (Ref. Bartlett data, and need to expose the data to broad ITC interpretation)
 - Use of empirical and historical data
- Why $10^{-4}/\text{yr}$ to $10^{-6}/\text{yr}$ Hazard Level Matters (in General) for NPP Safety Management
- Tsunami PRA Methodology, Safety Policy, and Value of PRA to the Public and Industry

Fallacies and Evaluation Gaps

Topics

- Potential Improvements and Advances in Regulatory and Industry Programs
- Potential Improvements and Advances in PG&E Studies for DCP
- Importance of Improvements
- Poorly Understood Context of Central CA Tsunami Hazard (particularly for Long Return Periods); and the Role of Data Collection and Appropriate Study

Some Fallacies

- Fallacy 1: Sewell believes, or believed, that DCPD is unsafe for tsunamis
 - Sewell's concerns have always been about proper safety evaluation and having a robust basis for suitable action and decisions for safety management, including the appropriate studies based on state-of-the-art methodology and confirmation by the ITC.
 - Sewell's 2003 study came at a time when: (a) a new state of the art and new recognitions about the general threat of tsunamis and SMFs had emerged; and (b) Sewell had been working intently with the tsunami science community and clients to improve the state of the art in hazard assessment and implement the improvements in practice
 - Sewell recognizes that it rightly takes some time for new methods and data to be digested into a revision of the state of the art, and sometimes longer, for practical implementation.
 - Sewell's concern for suitable tsunami hazard evaluation was properly heightened following the Tohoku tsunami and ensuing Fukushima event.
 - Sewell, or others, cannot have a rational basis for comment on DCPD tsunami safety until the appropriate studies are performed
 - Sewell does not yet know with high confidence what the outcome of proper studies will be, but anticipates that proper tsunami investigation, including hazard and PRA study, can reveal the actions, if any are needed, for achieving targeted (risk-consistent) tsunami safety of DCPD

Some Fallacies

- Fallacy 2: Establishing consistency with the Tsunami ITC can be side-stepped
 - Not properly considering the ITC and not assessing epistemic variations has generally led to, and will continue to lead to, unstable safety decisions
 - Sewell has proposed decision making based on “control charting” [Deming (1975)]; Shewart (1939)] of hazard and risk results – within well-assessed epistemic bounds – as a means for stabilizing safety management
 - Measure process stability, and keep process and process variation within acceptable limits
 - Avoiding expense of re-analysis and retrofits at an undue level
 - Explicitly account for costs of a threat as well as uncertainty about the threat
- Fallacy 3: Coordinating with tsunami inundation mapping programs and other programs is unimportant
 - Hierarchical consistency in safety policy applies

Some Fallacies

- Fallacy 4: 10^{-4} /yr is too remote of a concern, and there is no need to consider such annual probability levels, or lower
- Fallacy 5: Significant SMFs are not possible on shallow slopes
- Fallacy 6: Major events are not possible at our location of interest
 - Recall Cases of Columbia Shuttle; Fukushima; Katrina; Sandy; Etc.
- Fallacy 7: Strike slip faulting is ineffective as a SMF tsunami generator
 - Some of the largest historically observed SMFs and landslide tsunamis are verified as being triggered by earthquakes (of faulting style that is not subduction), and the largest paleo slides are believed to be triggered by earthquakes that were not subduction events.
 - Recent publications on the Haiti earthquake and tsunami not only state the relation of strike-slip faulting and tsunami generation for that event, but discuss the implications for strike-slip-triggered SMFs offshore California.

Some Fallacies

- Fallacy 8: It is clearly known that there is a sharp transition in SMF-generated tsunami hazard at Mendocino Triple Junction (MTJ), with the landslide tsunami threat diminishing markedly for latitudes below MTJ
- Fallacy 9: We know that offshore Central California is more stable compared to other coastlines that have experienced large SMFs and/or we know that only comparatively small SMFs can occur offshore Central California within annual probability levels of interest.

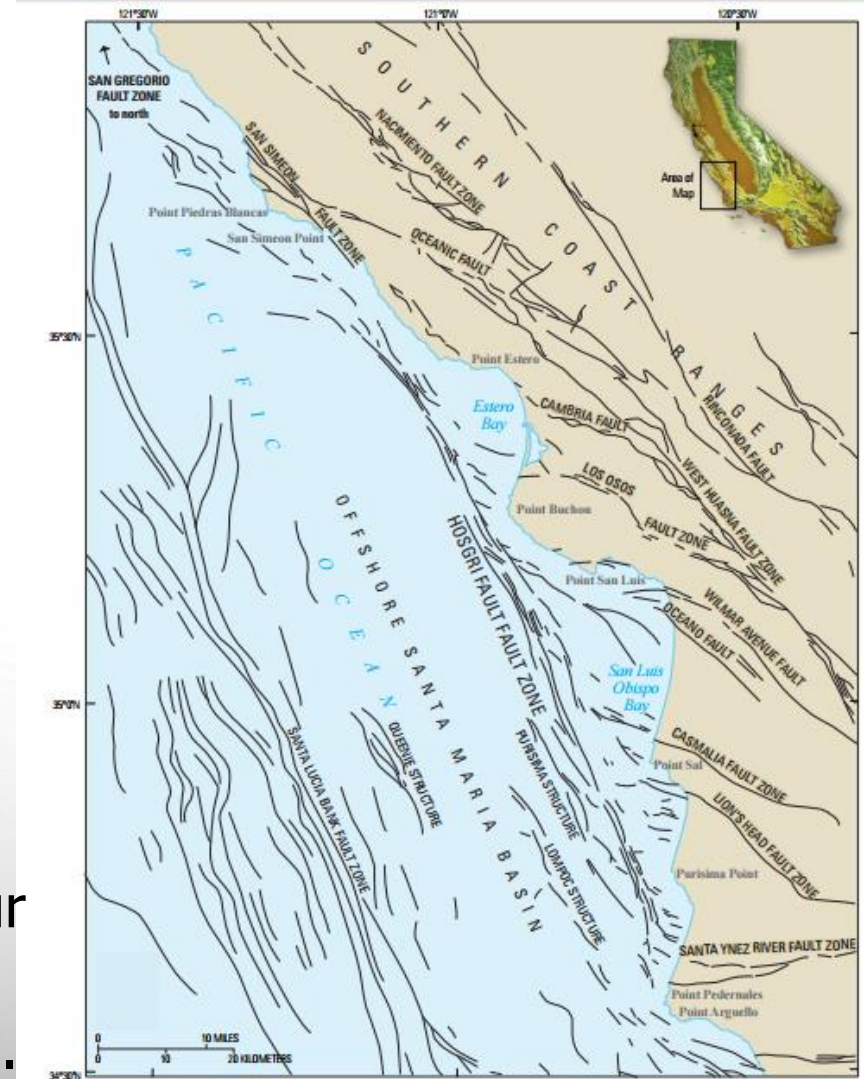


Figure 1. Fault traces in the offshore Santa Maria Basin and adjacent coastal California. The Hosgri Fault Zone forms the eastern boundary of the offshore Santa Maria Basin; the northern part is aligned with the strike-slip San Simeon/Sur/San Gregorio Fault System to the northwest (Lettis and others, 2004). The Hosgri Fault Zone is subparallel to the north-northwest trend of faults in the offshore Santa Maria Basin. However, the west-northwest trends of faults to the east of the Hosgri Fault Zone are abruptly terminated at the fault zone.

Some Fallacies

- Fallacy 10: Implications of Bartlett and other data are clear at this time and constrain the landslide tsunami hazard to a low level
- Fallacy 11: When formulating and evaluating hypotheses as to SMF source potential, paleo-data provide a more valid and sufficient basis for assessment of the hazard from future tsunamis, versus geotechnical properties (i.e., engineering mechanics properties of soil and rock) and slope stability analyses

Some Fallacies

- Fallacy 12: Regardless of the hazard, the risk at DCPD from tsunamis less than 85 ft is now known to be clearly negligible
 - 85 ft level of DCPD power block does provide good siting-based protection
 - However, induced failures, random failures on demand (in relation to safety relevant SSCs), access/response problems and operator errors are yet possible for tsunamis lower than the power block
 - CCDPs for various cases are non-zero, can be determined, and should be included (for all tsunami levels) as part of a complete tsunami risk study
 - For a nominal 85-ft tsunami wave, occurrence of significant wave and debris splash-up and spray (i.e., real physical phenomena not included in nominal amplitude assessments) can be expected to occur. Although the splash-up does not carry the same impact and flooding potential of the full-momentum in the nominal wave level, local adverse impact effects and flooding are still possible
 - In the case of Fukushima, the nominal wave height was about 14 m (~50 ft) whereas the height of the wave splash-up as it impacted leading power structures was approximately three times that level (~42 m, or ~150 ft)
 - Consideration of splash-up and spray effects are requirements of risk evaluation included in the most recent draft revision of the ASME-ANS JCNRM PRA Standard

Some Fallacies

- Fallacy 13: We have clear understanding as to the possible bounds (upper limits) of tsunamis and the range of tsunami characteristics that need to be considered
 - Upper bounds are established based on physical maximums (e.g., now well-established studies examine maximum ground motion from earthquakes, as well as maximum magnitudes), which are often poorly understood
 - Although we must assess upper bounds in probabilistic hazard analysis, when considering hazard results in safety management, for apparent reasons, we are typically not concerned with extinction level events (ELEs), which are $\sim O(10^{-8})$ /yr annual probability [equivalently, $\sim O(10^8)$ yr return period)] events
 - For a hazard study to be complete (particularly for critical facilities), and most useful for PRA, it must assess hazard and its uncertainty to about 10^{-7} /yr mean annual probability levels, explicitly and quantitatively explaining physical possibilities and likelihoods even to very extreme levels
 - Viewed differently: consider any and all tsunami run-up levels X of interest at a given site, but suppose as one instance we examine $X=100$ ft. The ITC should seek to hypothesize potential scenarios of wave run-up at this level, and if it cannot rule out such scenarios as clearly being physically impossible, then such scenarios and estimates of their likelihoods must be made. Once a proper synthesis of all possible scenarios for all levels is made according to detailed PTHA formulation, then the scenarios at any level X of interest, and above, can be discounted as negligibly important only if the annual frequency of exceeding X , up to high confidence level (e.g., 95%) is found to be less than 10^{-7} .

2016 Insights and Updated Conclusions

- General Summary
- Sewell (2003) revisited – What remains valid; what perhaps does not (i.e., How should we use it, and move on to further progress?)
- Revisit of Lessons Learned and Value of PRA
- Update of Principal Recommendations and Conclusions for Use by DCISC and Stakeholders