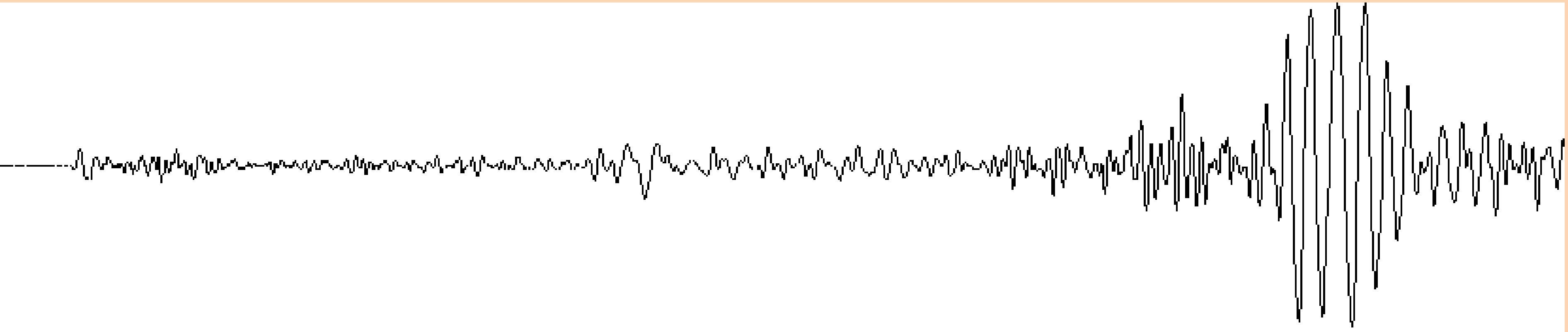


Scientific Lessons Learned From Arabian Gulf Earthquakes

الدروس العلمية المستفادة من زلازل منطقة الخليج العربي

Abdullah M. Alamri

Seismic Studies Center, King Saud Univ.

•

Why did the earthquake occur?

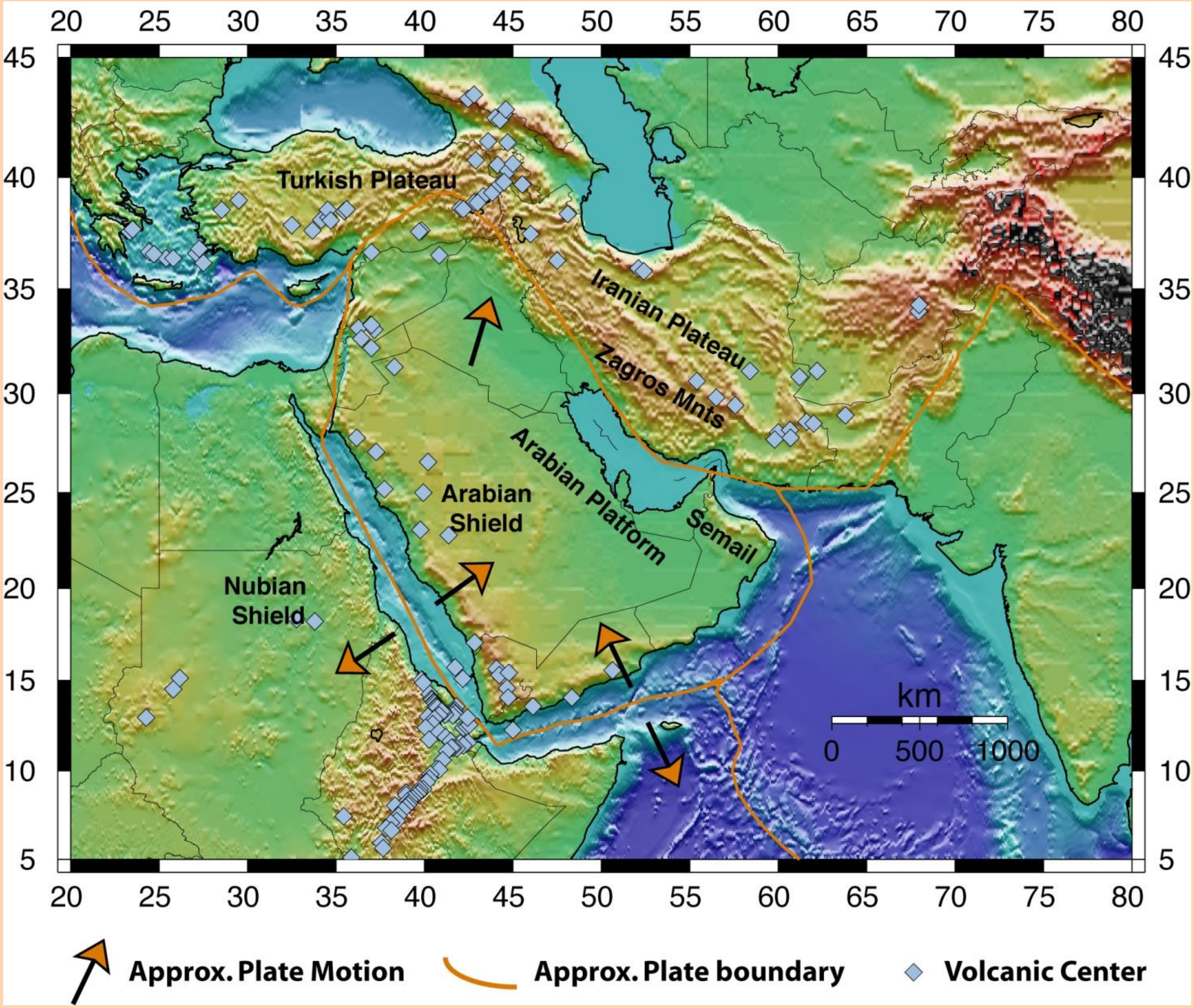
- Iran is situated on a destructive plate boundary between the Arabian plate and the Eurasian plate.
- The Arabian plate is moving northwards into the Eurasian plate at a rate of 3cms per year.
- Stresses build up in the crust which are eventually released in the form of seismic energy
- The seismic energy, in the form of primary and secondary earthquake waves ,cause the surface of the earth to deform.
- The ground movement causes buildings to collapse and communications to be damaged.

Tectonic Framework of the Arabian Gulf

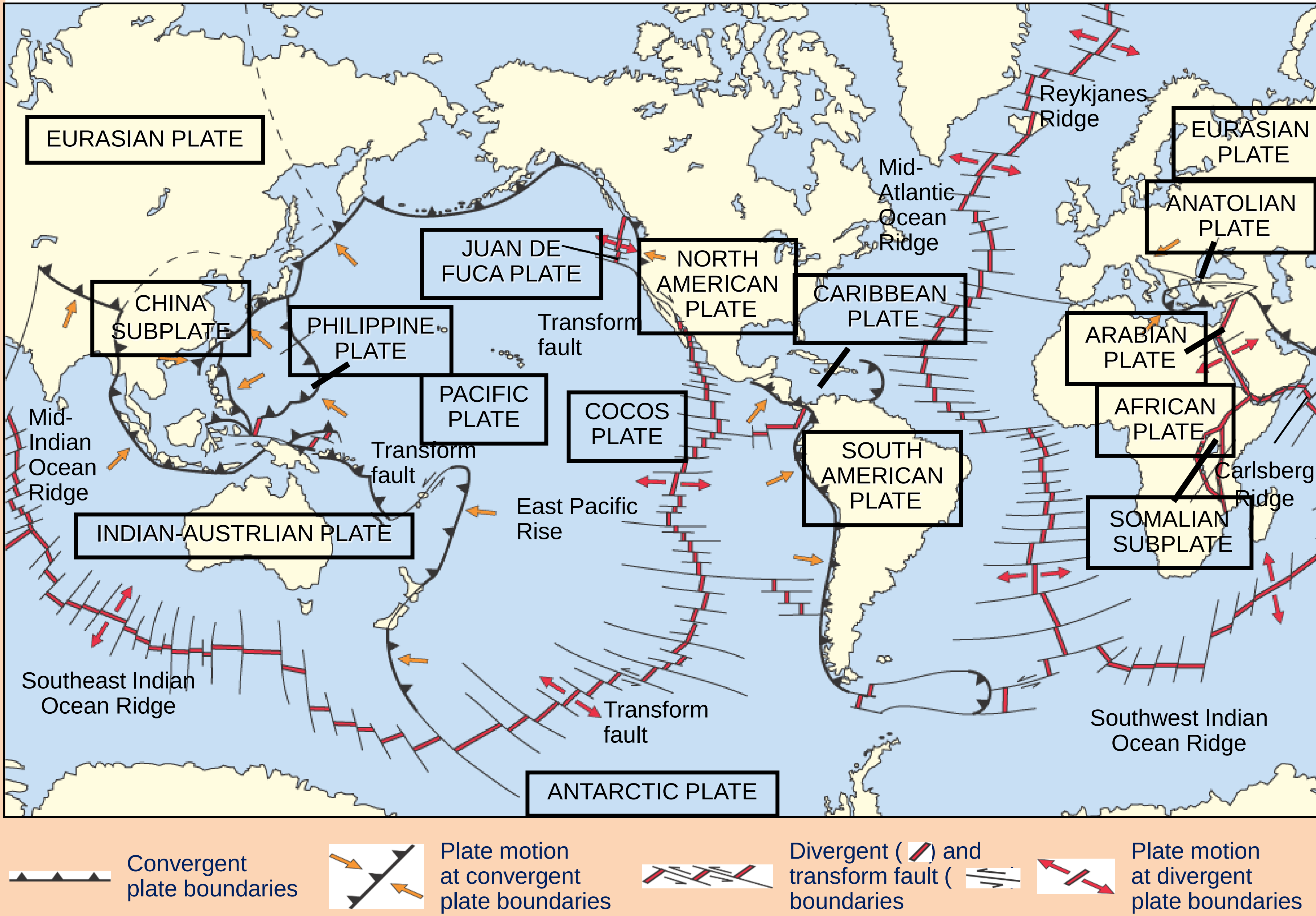
Convergence of the Arabian Plate with the southern Eurasian margin forms the Zagros Mountains.

Arabian Gulf is underlain by continental lithosphere.

The northern UAE and Musandam Peninsula mark a structural transition between the Semail Ophilite and the Arabian Platform.

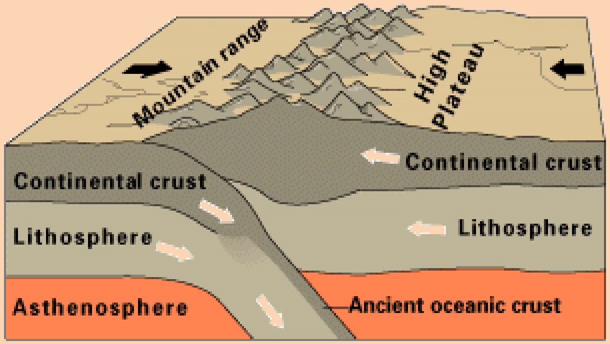


© 2002 Brooks/Cole - Thomson Learning

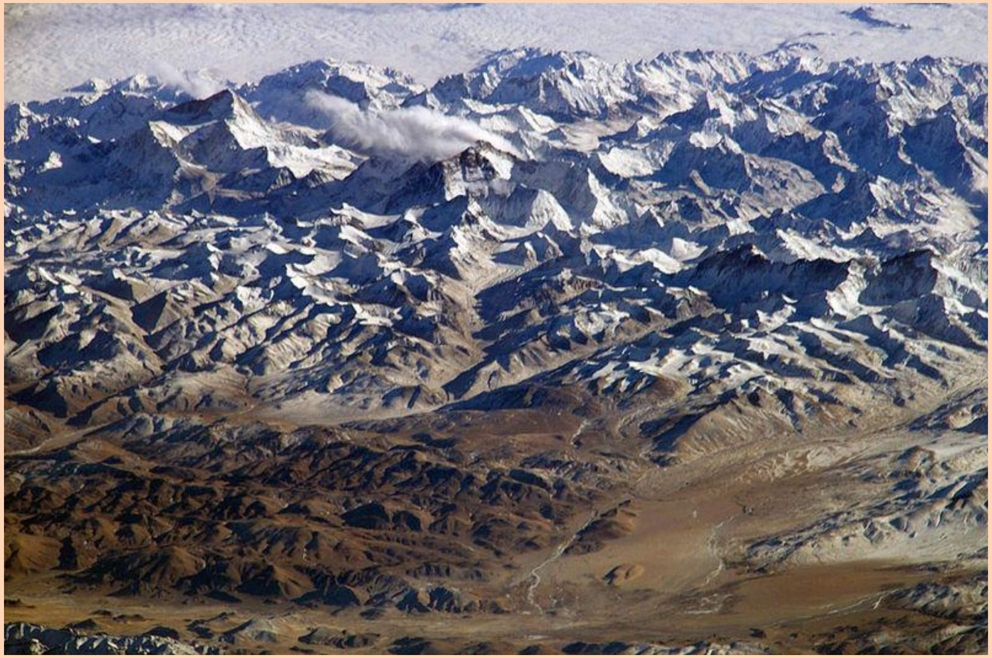


CONVERGENT BOUNDARIES
plates colliding

Continent-continent convergence:
Folded mountains



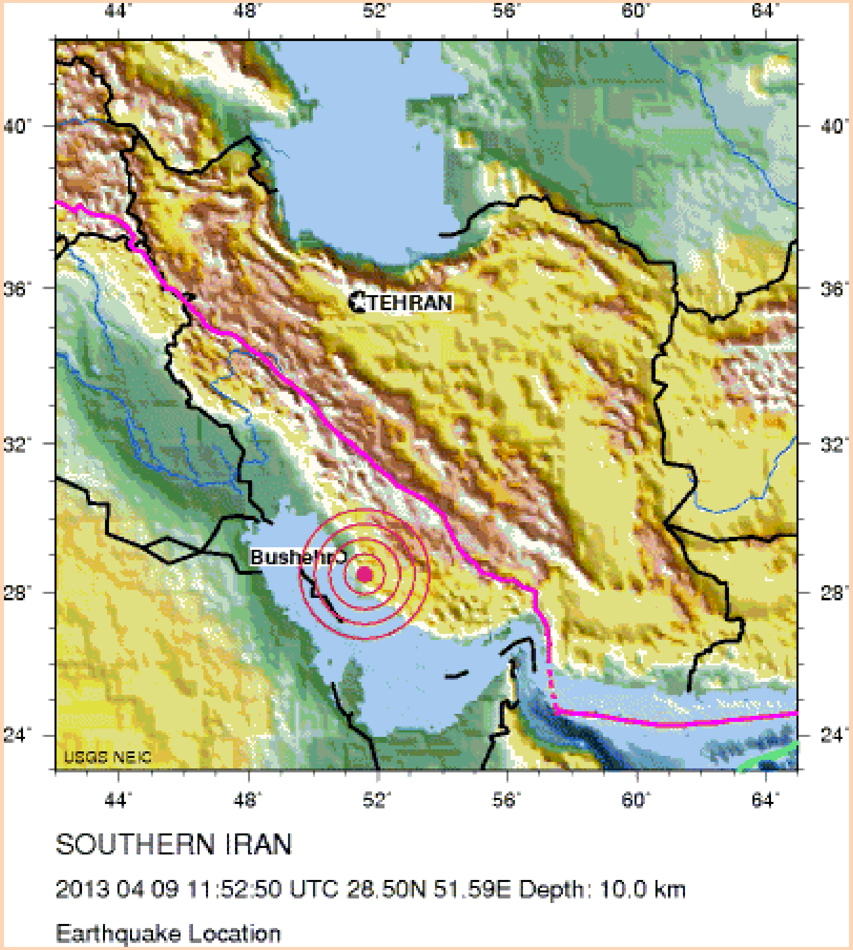
Ex Himalayas
Eurasian/Indian plates



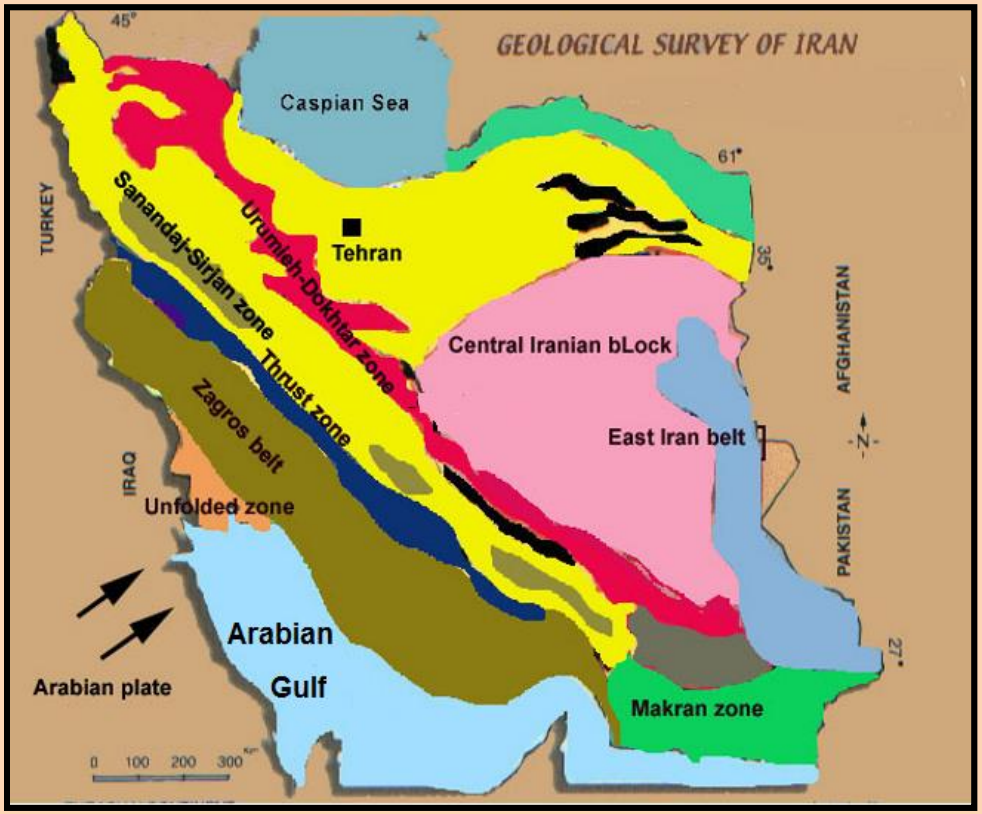
Collision Plate Boundary

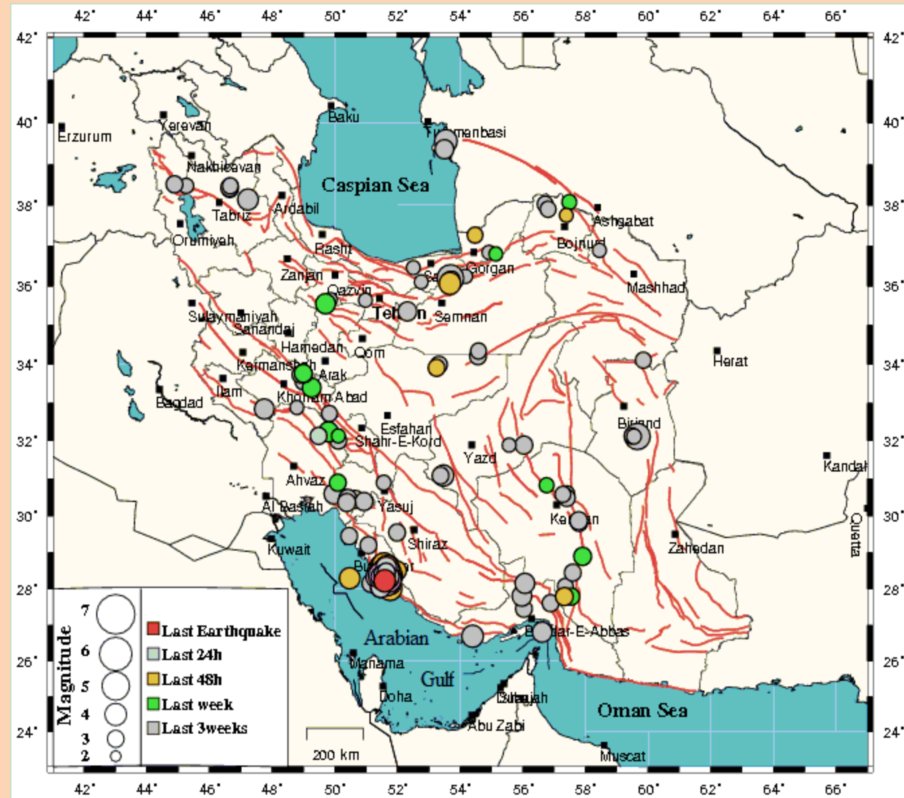
Location

Magnitude	**6.3** (Mw)
Date-Time	**Tuesday, April 09, 2013 at 11:52:50 UTC**
Location	28.500°N, 51.591°E
Depth	10 km (6.2 miles)
Region	**SOUTHERN IRAN**
Distances	89 km (55 miles) SE of **Bandar Bushehr, Iran** 272 km of **Dammam** 252 Km **Al-Jubail** 272 Km of **Manama (Bahrain)** 354 Km of **Doha (Qatar)**
Location Uncertainty	horizontal +/- 14.2 km (8.8 miles); depth +/- 2.8 km (1.7 miles)
Parameters	NST=156, Nph=157, Dmin=>999 km, Rmss=0.76 sec, Gp= 25°,

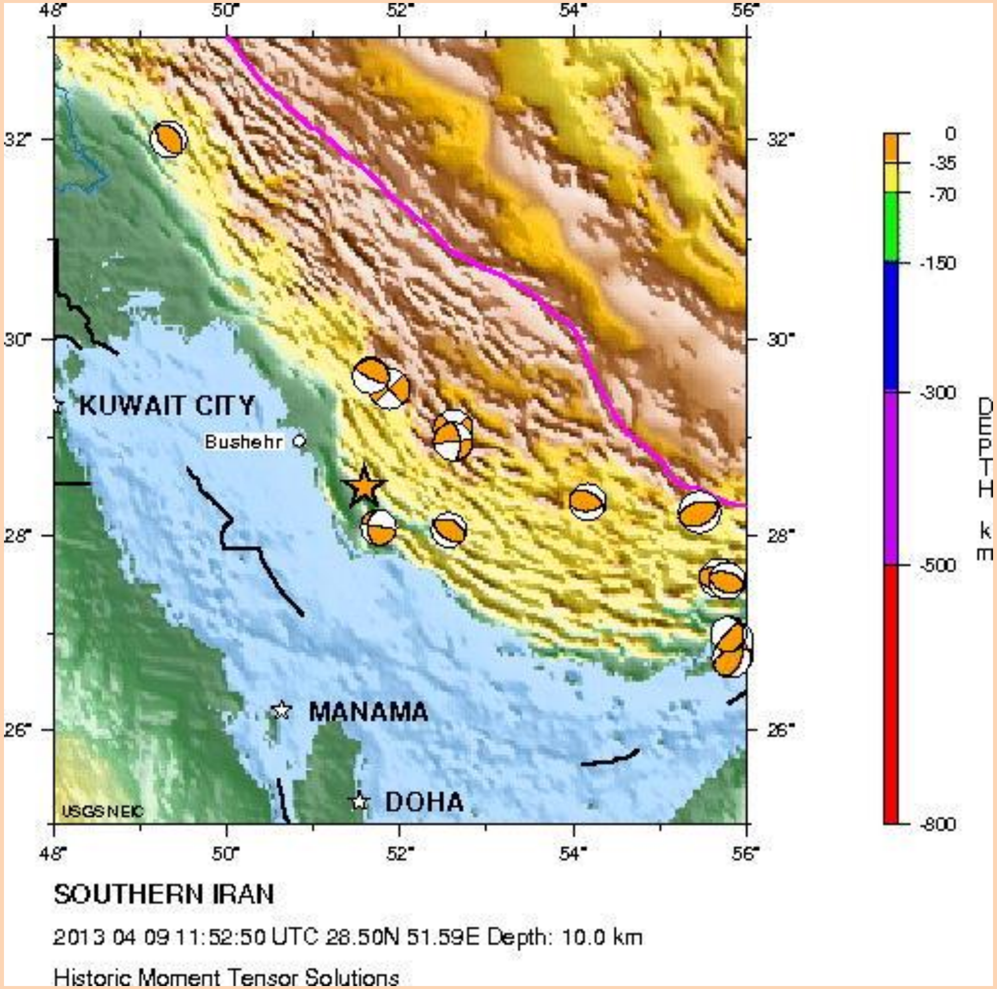


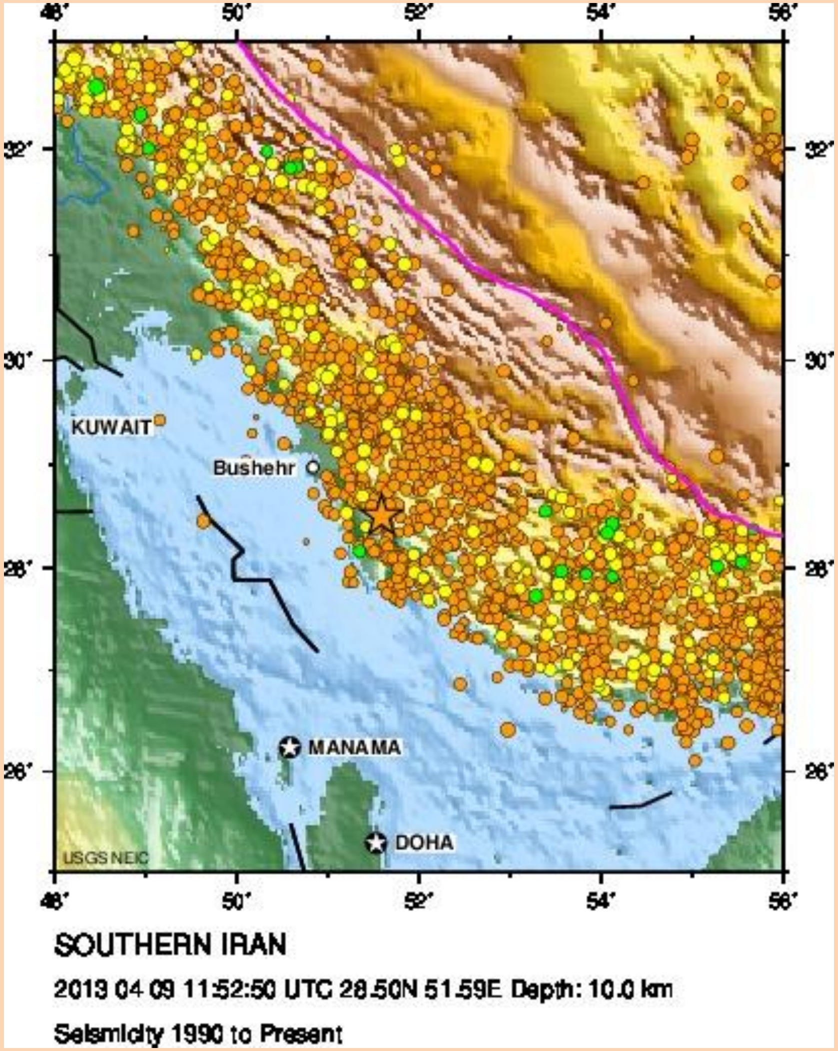
Geological Setting of Iran

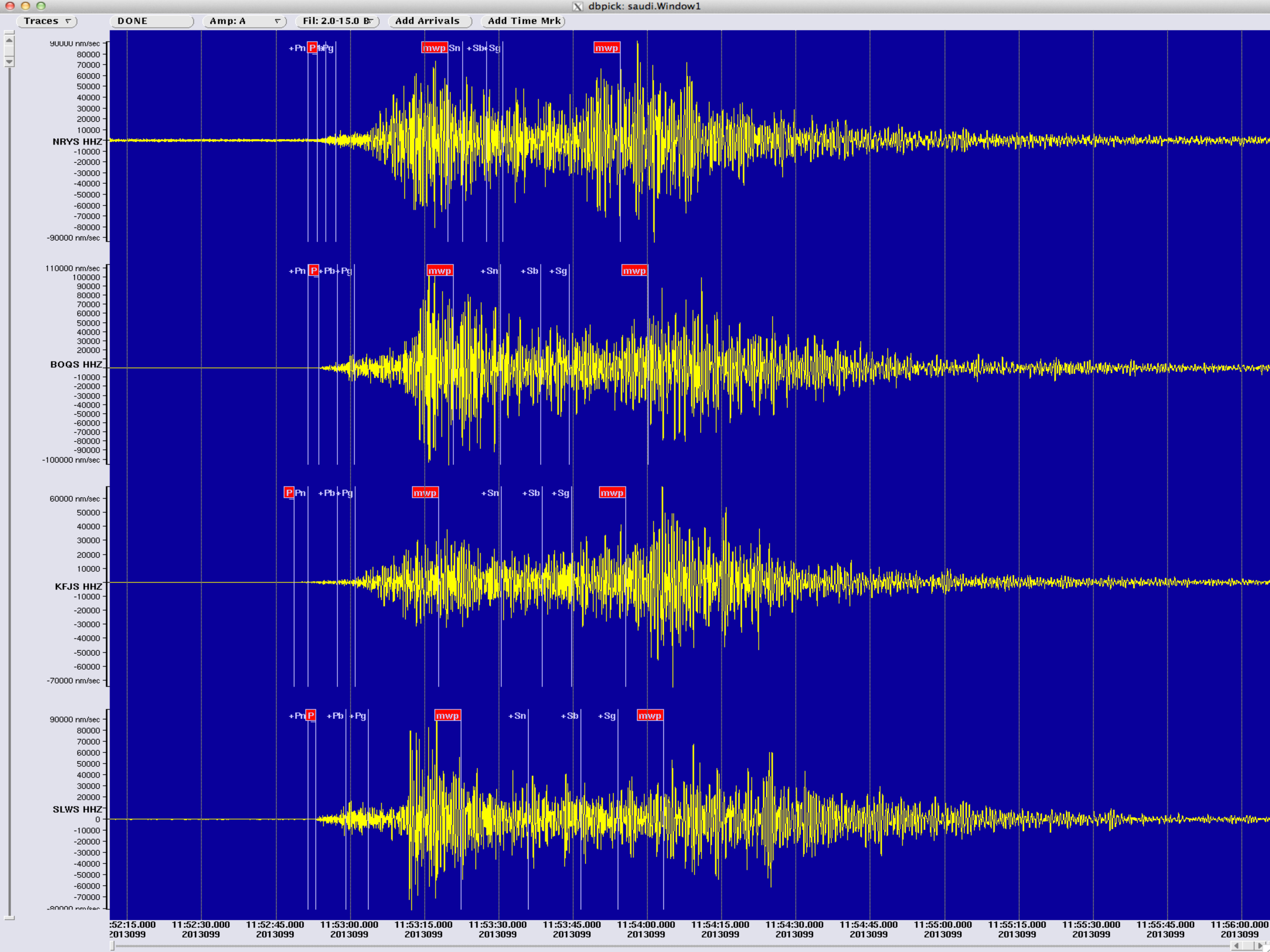




Historical Seismicity of Iran



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-100000 nm/sec
KFJS HHZ
60000 nm/sec
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SLWS HHZ
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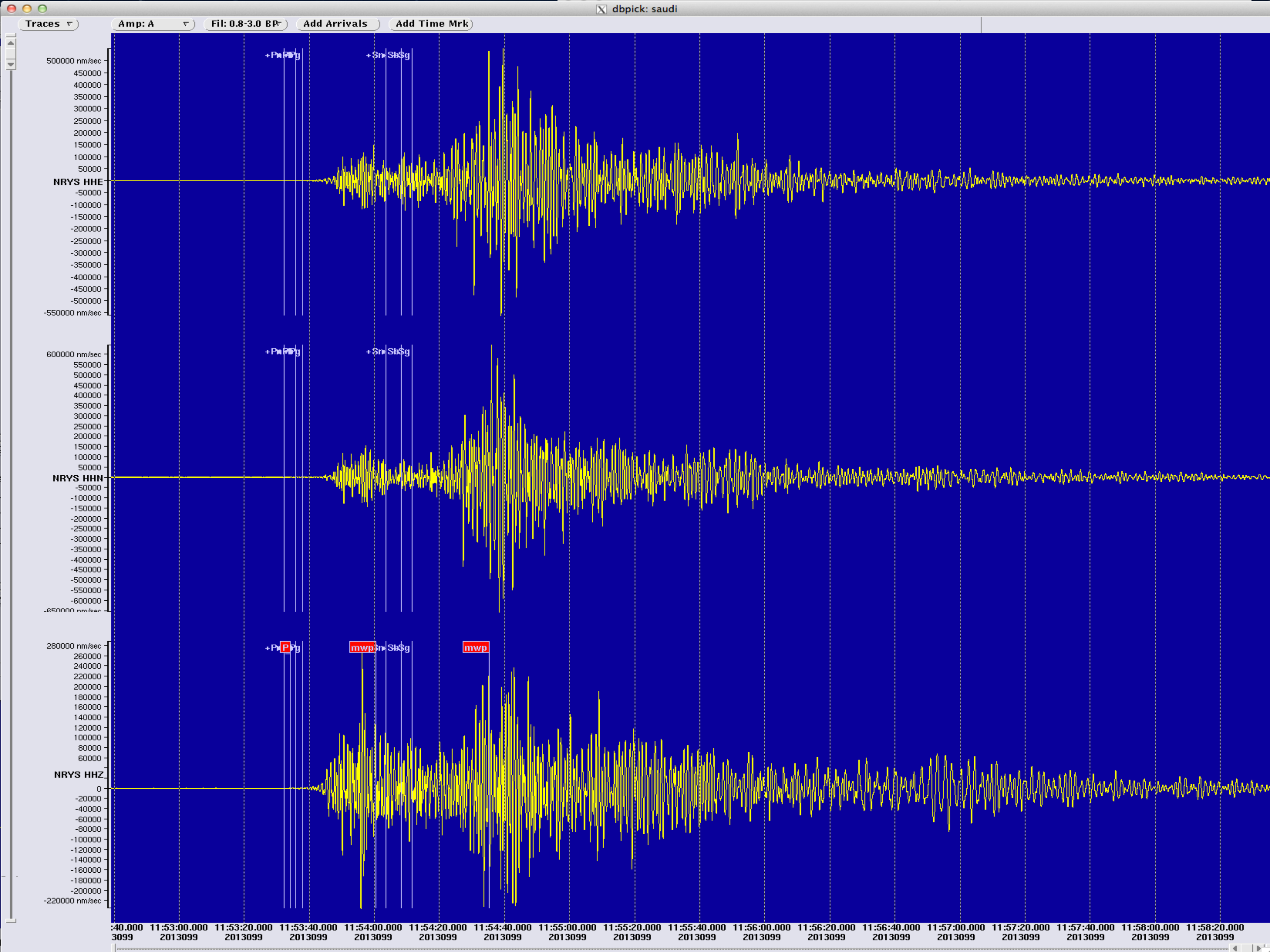
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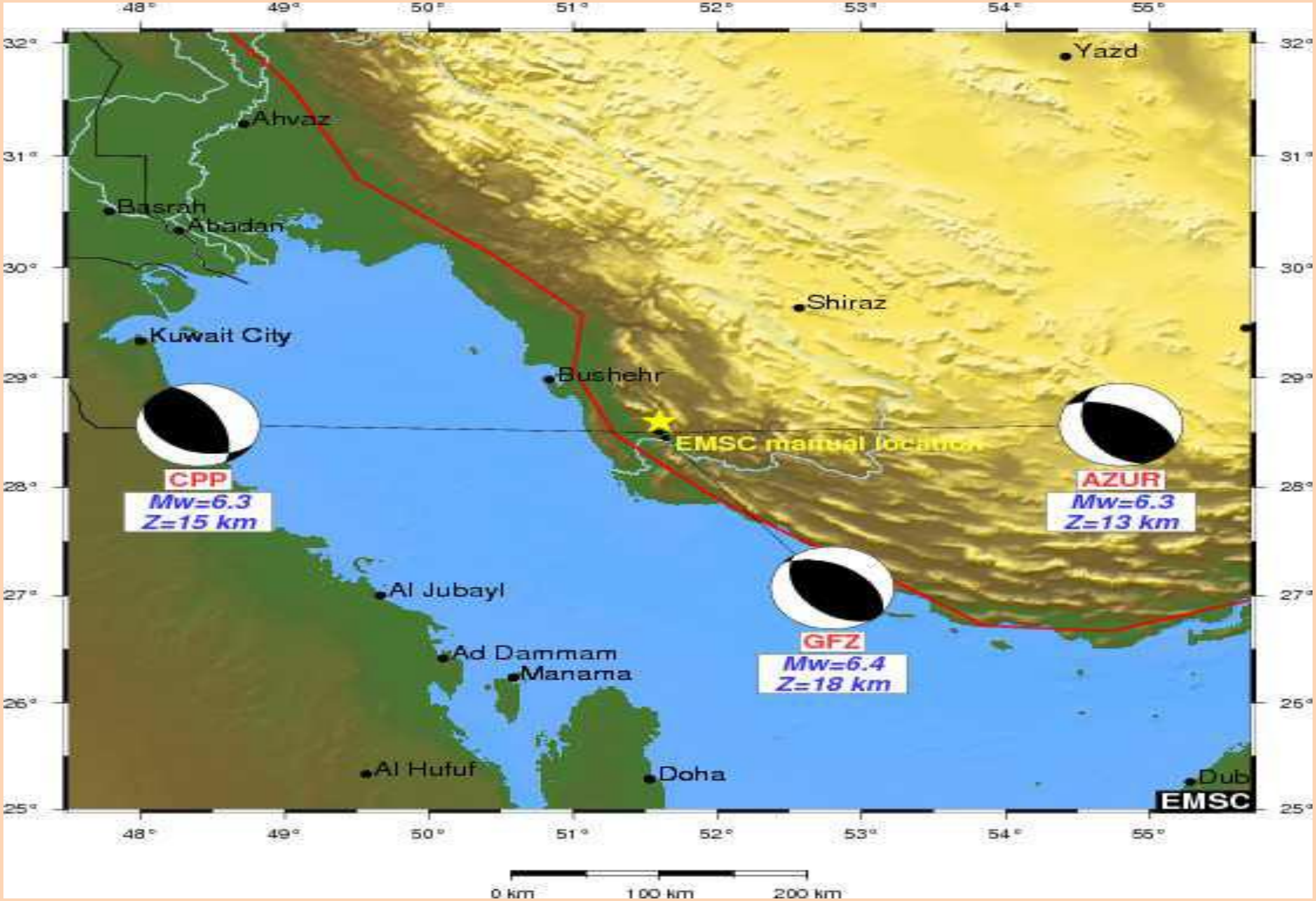
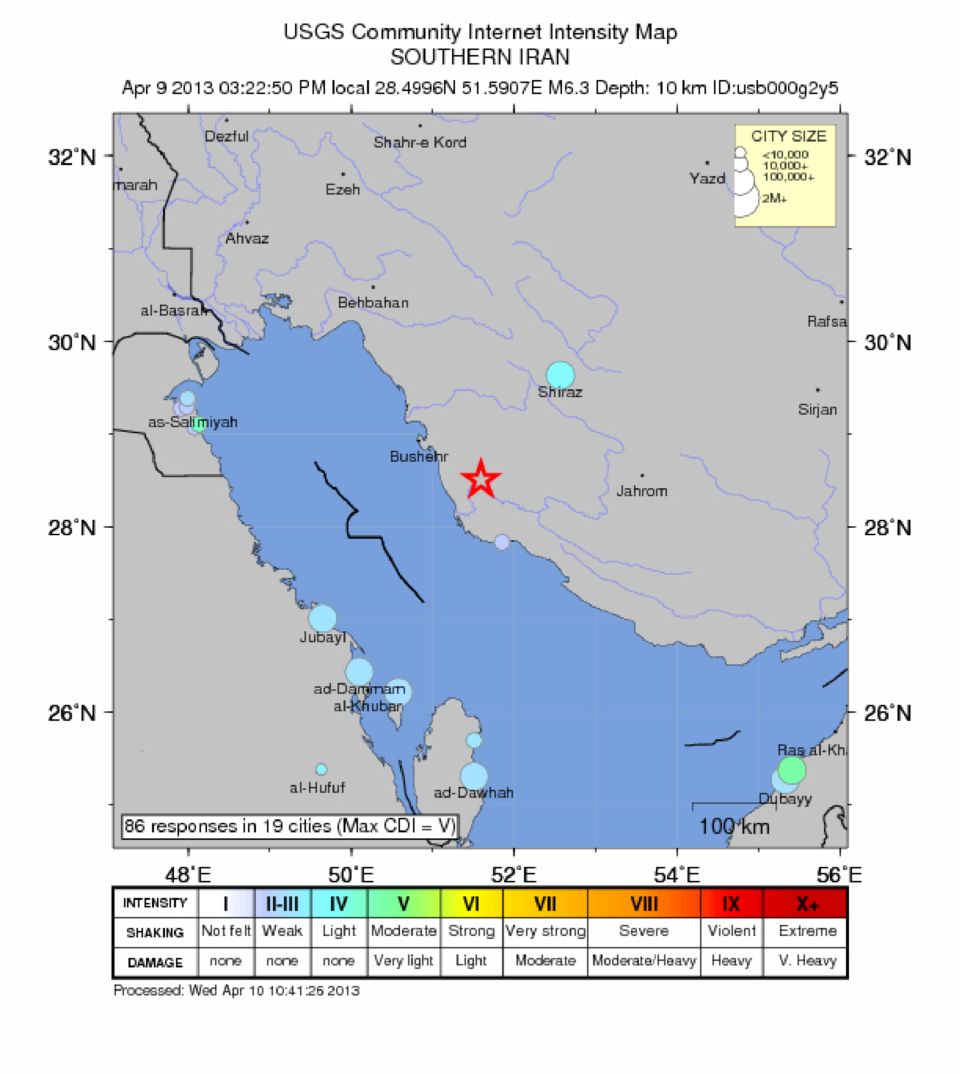
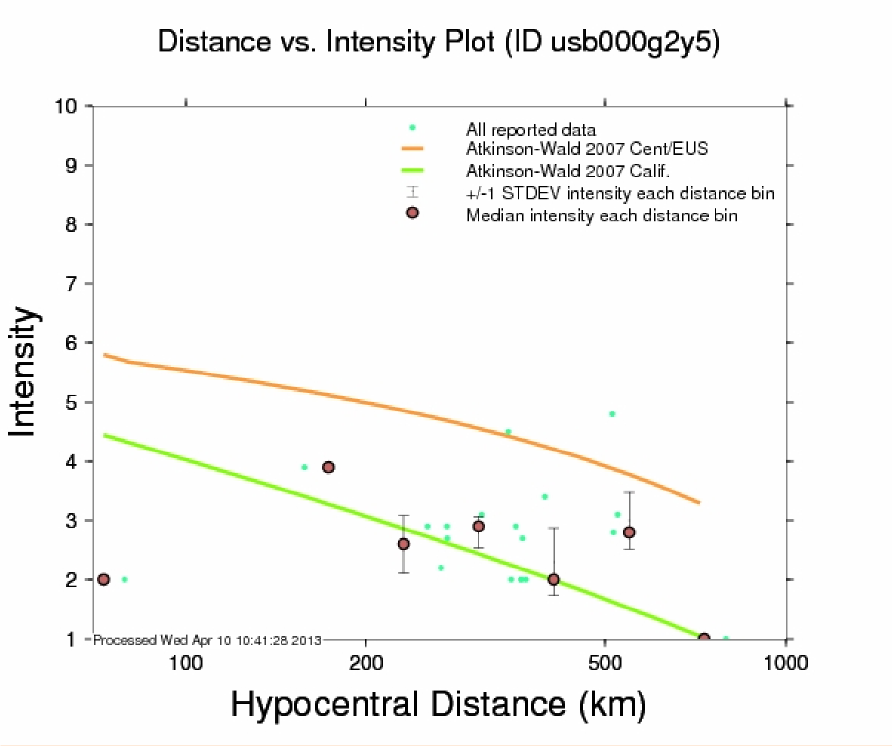


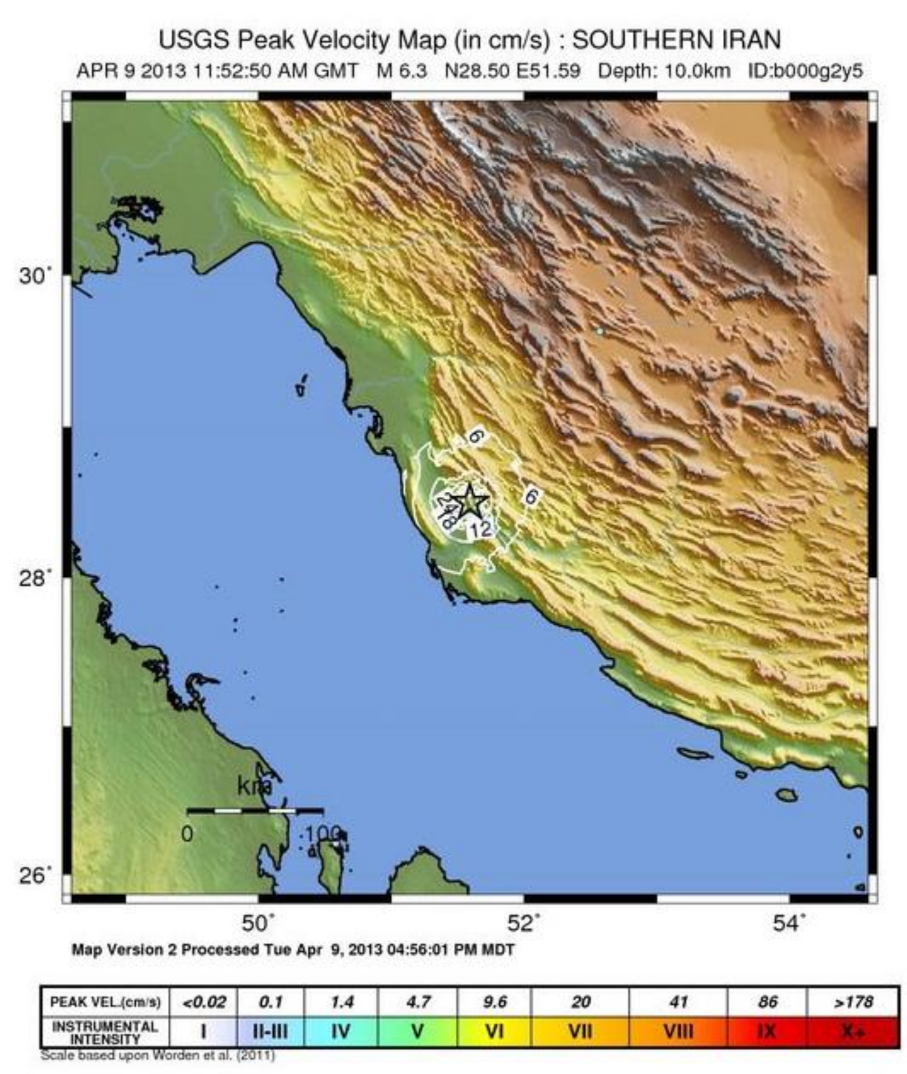
Yazd
Ahvaz
Basrah
Abadan
Shiraz
Kuwait City
Bushehr
EMSC manual location
CPP
Mw=6.3
Z=15 km
AZUR
Mw=6.3
Z=13 km
GFZ
Mw=6.4
Z=18 km
Al Jubayl
Ad Dammam
Manama
Al Hufuf
Doha
EMSC
0 km
100 km
200 km

Intensity Distribution of April 9, 2013





PGA & PGV


USGS Peak Velocity Map (in cm/s) : SOUTHERN IRAN
APR 9 2013 11:52:50 AM GMT M 6.3 N28.50 E51.59 Depth: 10.0km ID:b000g2y5
30˚
28˚
26˚
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km
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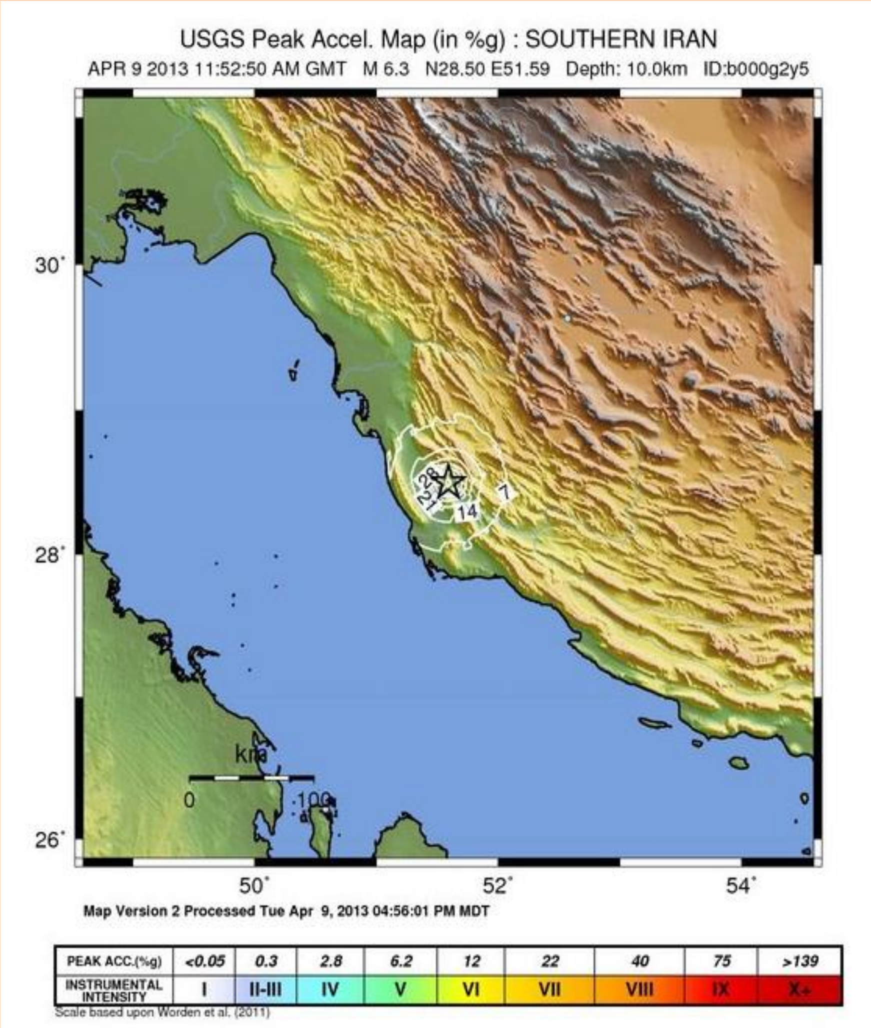
Map Version 2 Processed Tue Apr 9, 2013 04:56:01 PM MDT
PEAK VEL.(cm/s) <0.02 0.1 1.4 4.7 9.6 20 41 86 >178
INSTRUMENTAL INTENSITY I II-III IV V VI VII VIII IX X+
Scale based upon Worden et al. (2011)


USGS Peak Accel. Map (in %g) : SOUTHERN IRAN
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30˚
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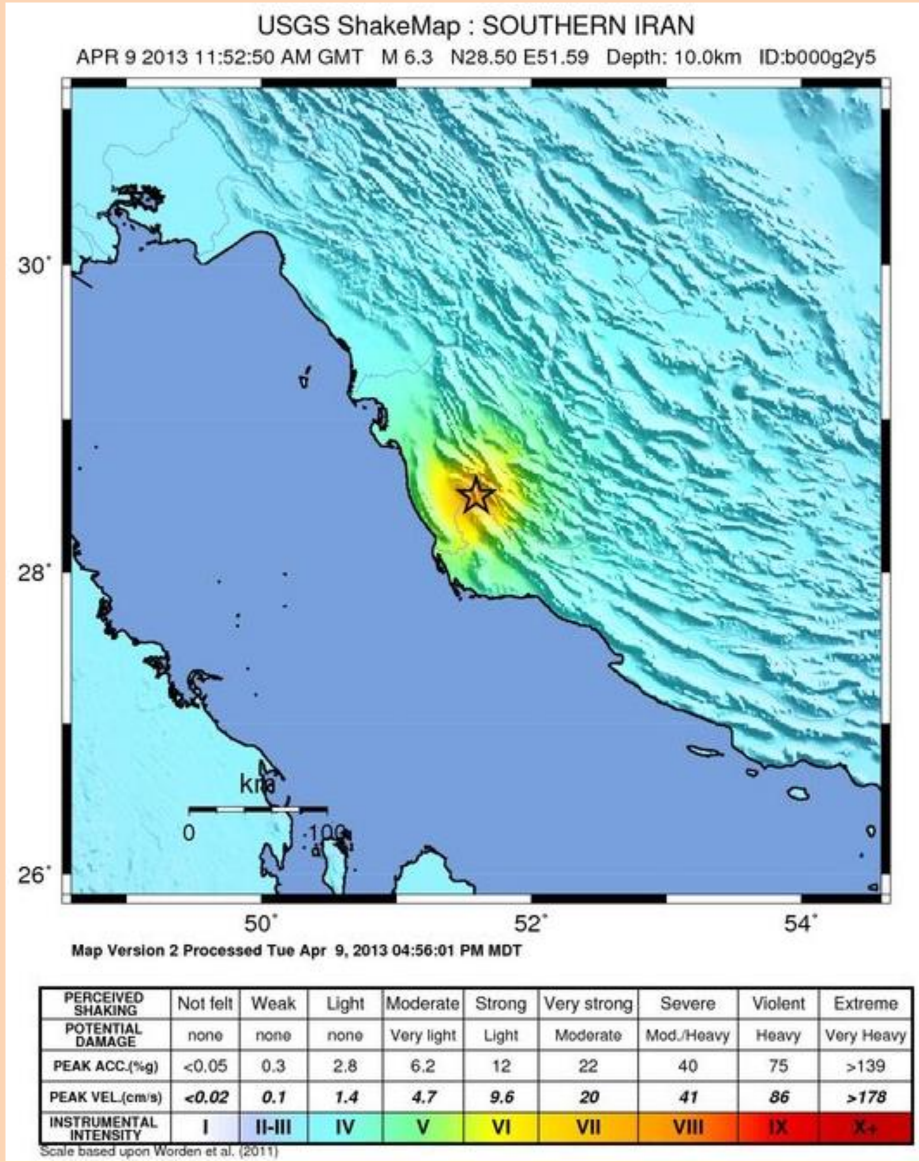
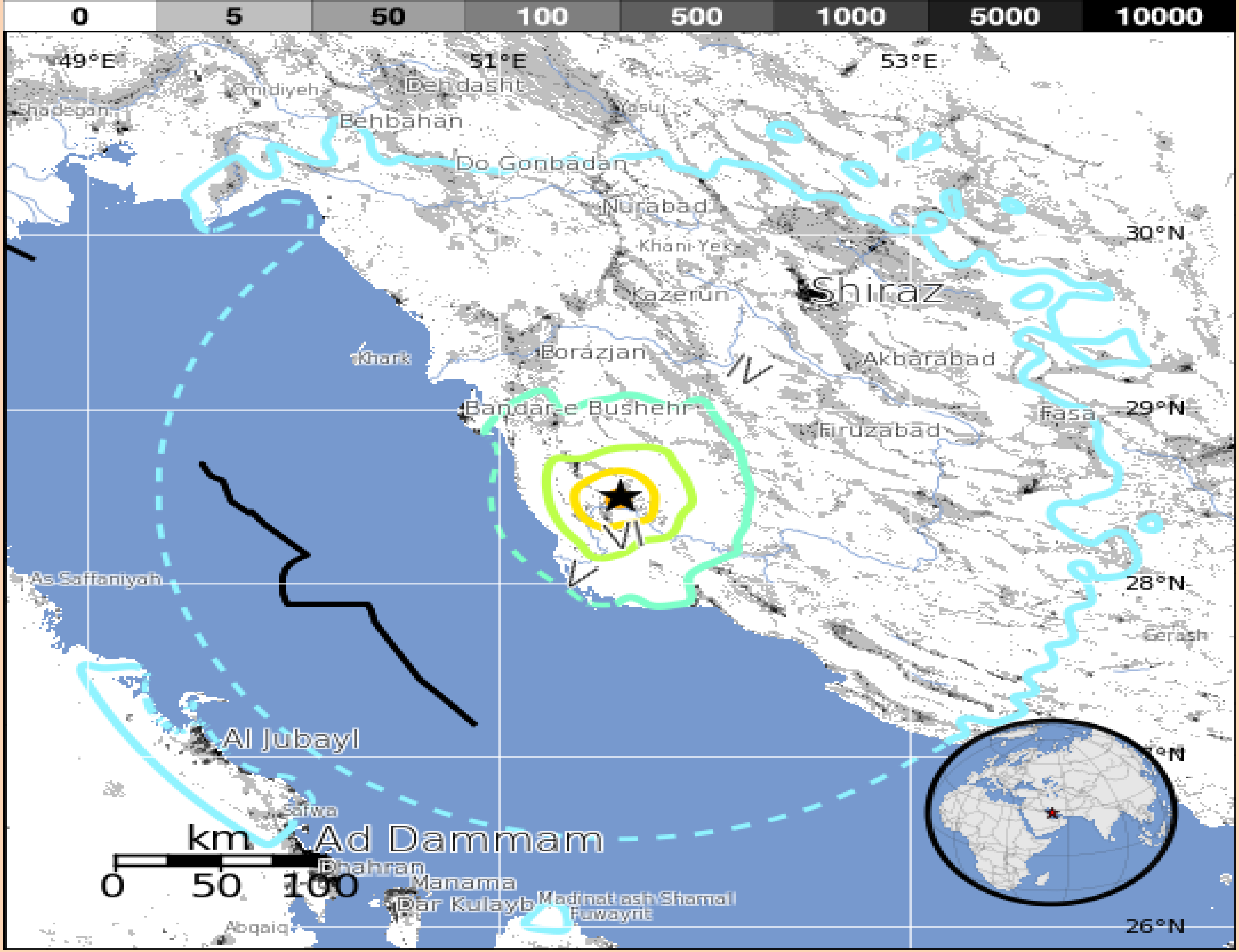
26˚
50˚
52˚
54˚
km
0
100
Map Version 2 Processed Tue Apr 9, 2013 04:56:01 PM MDT
PEAK ACC.(%g) <0.05 0.3 2.8 6.2 12 22 40 75 >139
INSTRUMENTAL INTENSITY I II-III IV V VI VII VIII IX X+
Scale based upon Worden et al. (2011)

Shake map


USGS ShakeMap : SOUTHERN IRAN
APR 9 2013 11:52:50 AM GMT M 6.3 N28.50 E51.59 Depth: 10.0km ID:b000g2y5
30˚
28˚
26˚
50˚
52˚
54˚
km
0
100
Map Version 2 Processed Tue Apr 9, 2013 04:56:01 PM MDT
PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme
POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Mod./Heavy | Heavy | Very Heavy
PEAK ACC.(%g) | <0.05 | 0.3 | 2.8 | 6.2 | 12 | 22 | 40 | 75 | >139
PEAK VEL.(cm/s) | <0.02 | 0.1 | 1.4 | 4.7 | 9.6 | 20 | 41 | 86 | >178
INSTRUMENTAL INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+
Scale based upon Worden et al. (2011)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5000
10000
49°E
51°E
53°E
30°N
29°N
28°N
26°N
Dehdasht
Omidiyeh
Shadegan
Behbahan
Yasuj
Do Gonbadan
Nurabad
Khani Yek
Shiraz
Kazerun
Khark
Borazjan
Akbarabad
IV
Bandar-e Bushehr
Fasa
Firuzabad
VI
V
As Saffaniyah
Gerash
Al Jubayl
Safwa
km
Ad Dammam
0
50
100
Dhahran
Manama
Dar Kulayb
Madinat ash Shamal
Fuwayrit
Abqaiq

Seismic Hazard

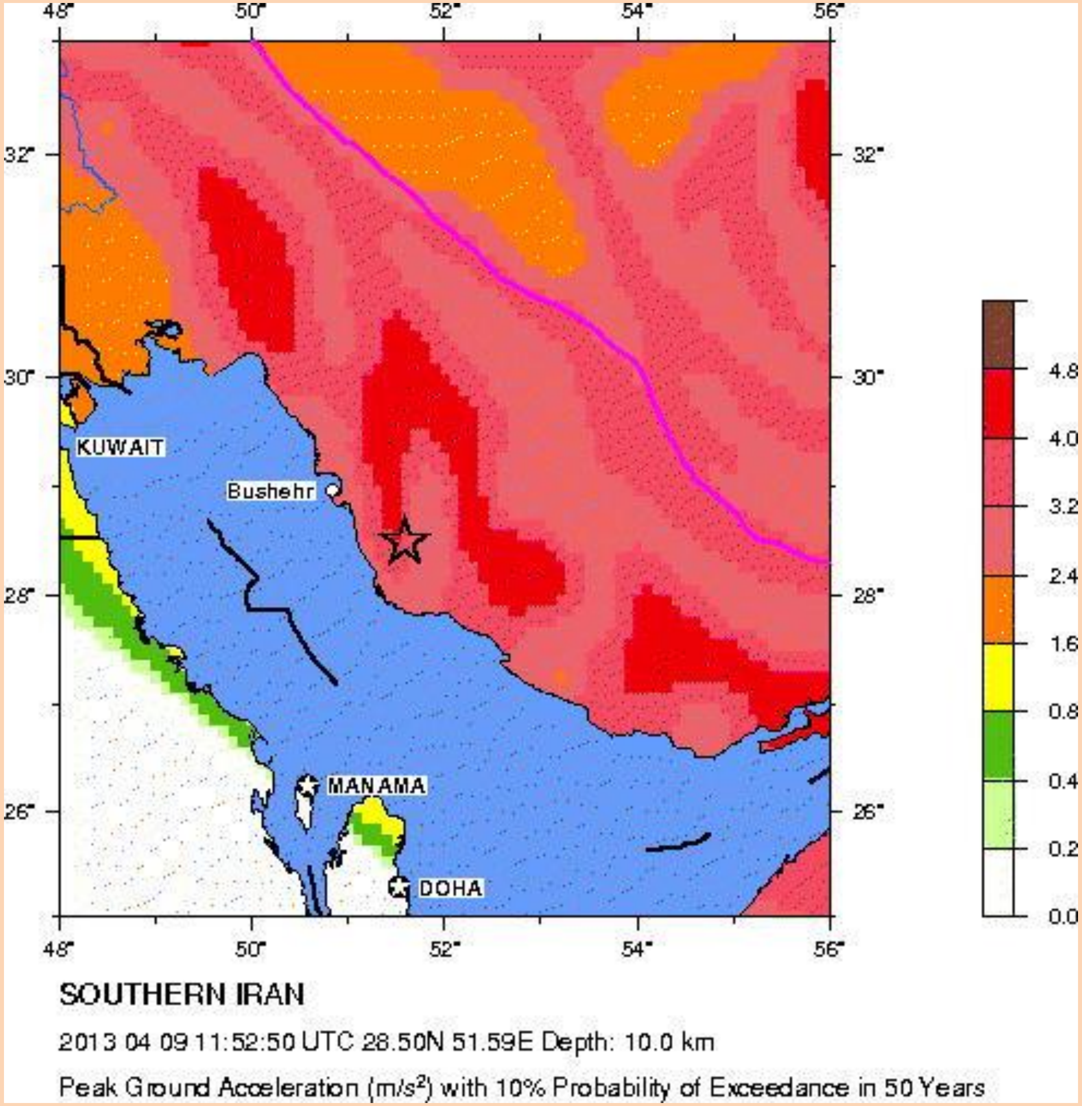
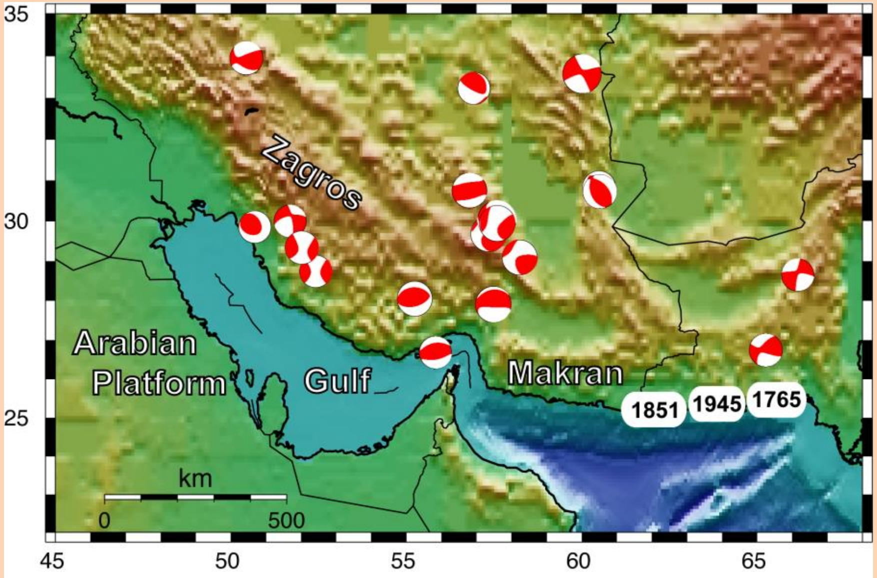


PHOTO: MOHAMMAD SALEHINIA

Seismicity of Gulf Region

Large Earthquakes (M_W 6.0) 1980-present (Harvard CMT)

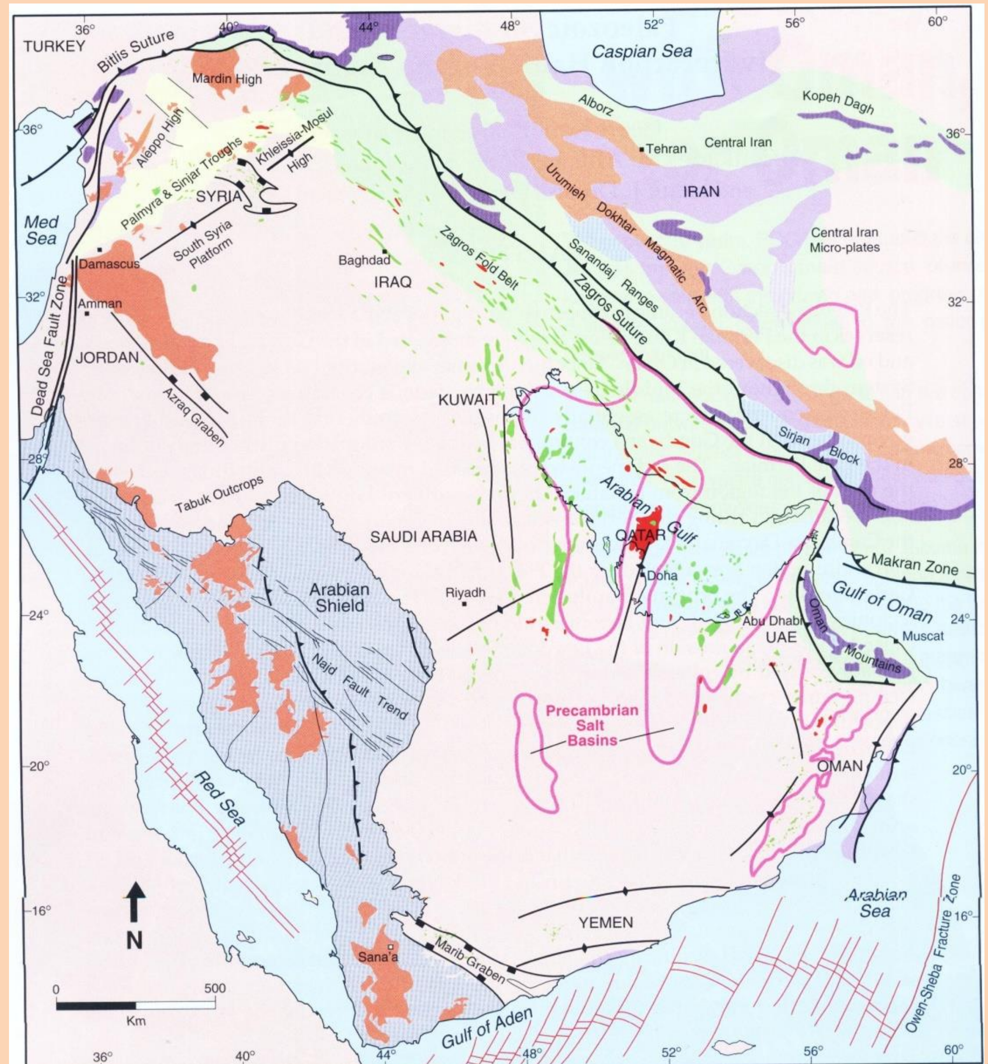


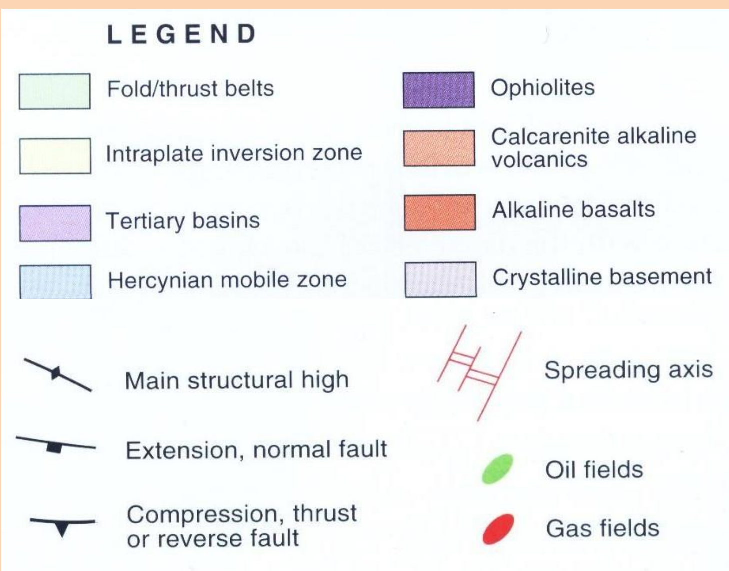
Zagros Thrust-and-Fold Belt has many large earthquakes

Great earthquakes have occurred along the Makran Thrust, including the 1945 M_W 8.1 event

Geology of the Gulf Region

Gulf is underlain by a large sedimentary basin



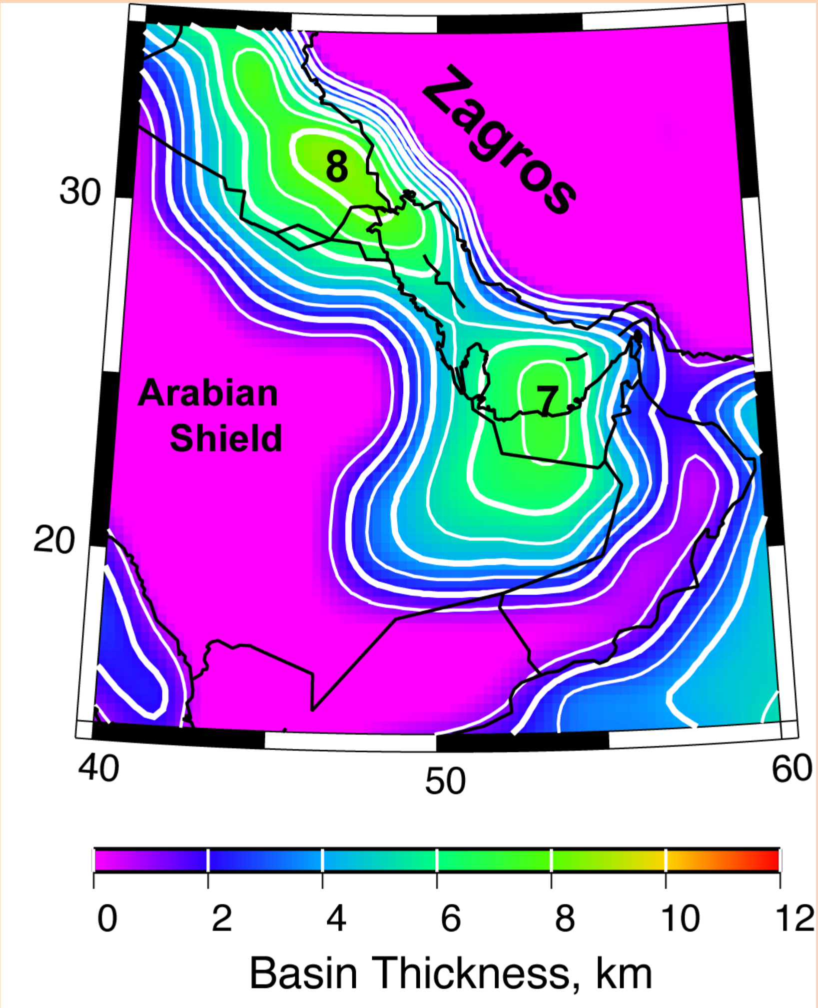


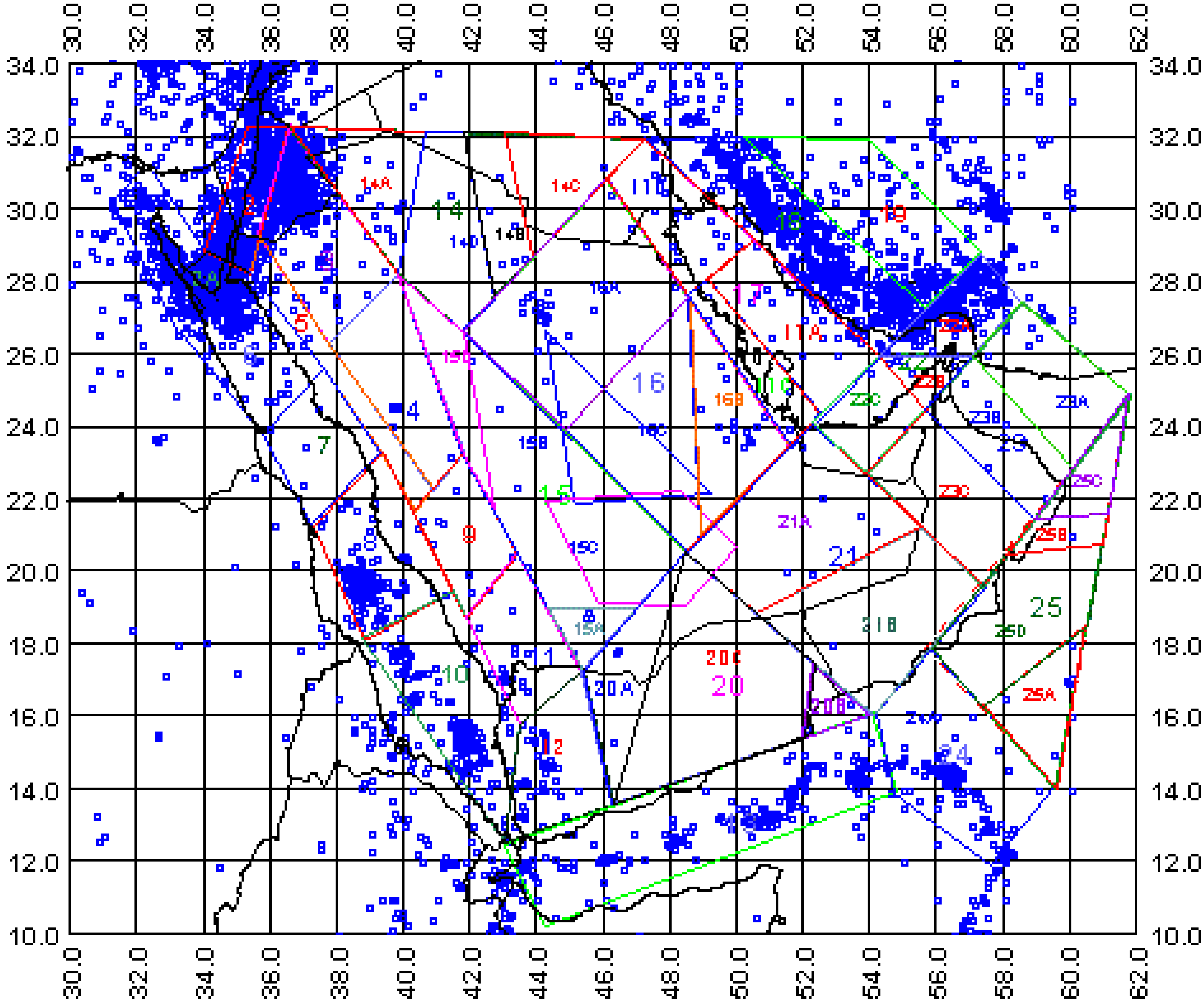
Sedimentary Basin Structure in the Gulf is Very Deep

This resulted from sedimentary deposition associated with the Tethys Sea and recent uplift of the Zagros Mountains

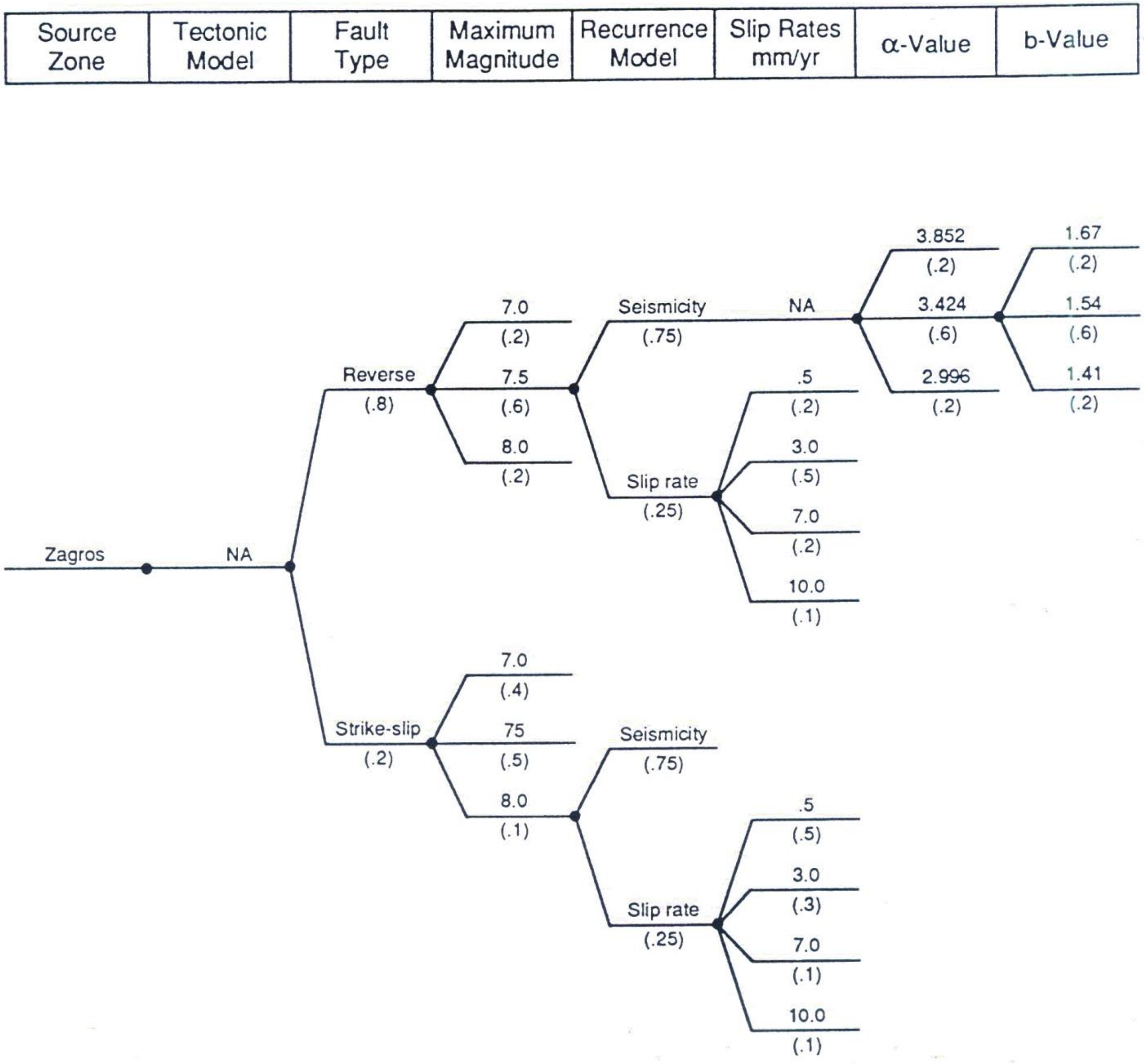
Seismic velocities within the Gulf sediment structure are **very low**

Basin structure "**traps**" and "**amplifies**" seismic waves





14A
14C
11C
14
14D
14B
18
19
15A
17
11A
16
15B
11B
4
7
15B
16C
23A
23B
23C
15
21A
9
15C
21
20.0
25
15A
31B
25D
11
20C
20
20A
20B
25A
24
12



Source Zone Logic Tree for the Zagros Collisional Belt

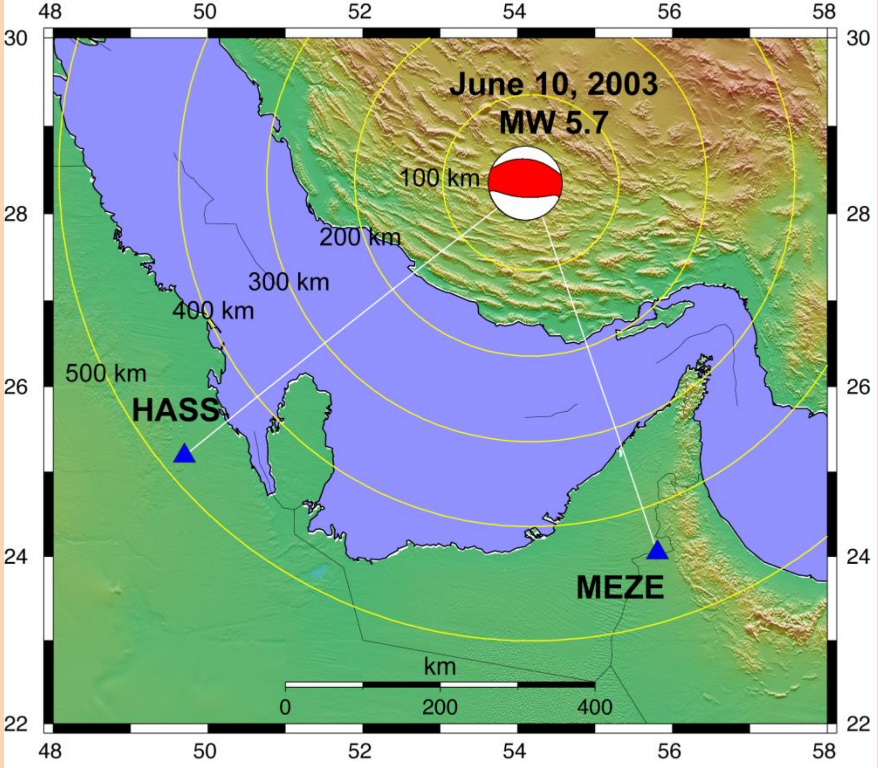
Source Zone Logic Tree for

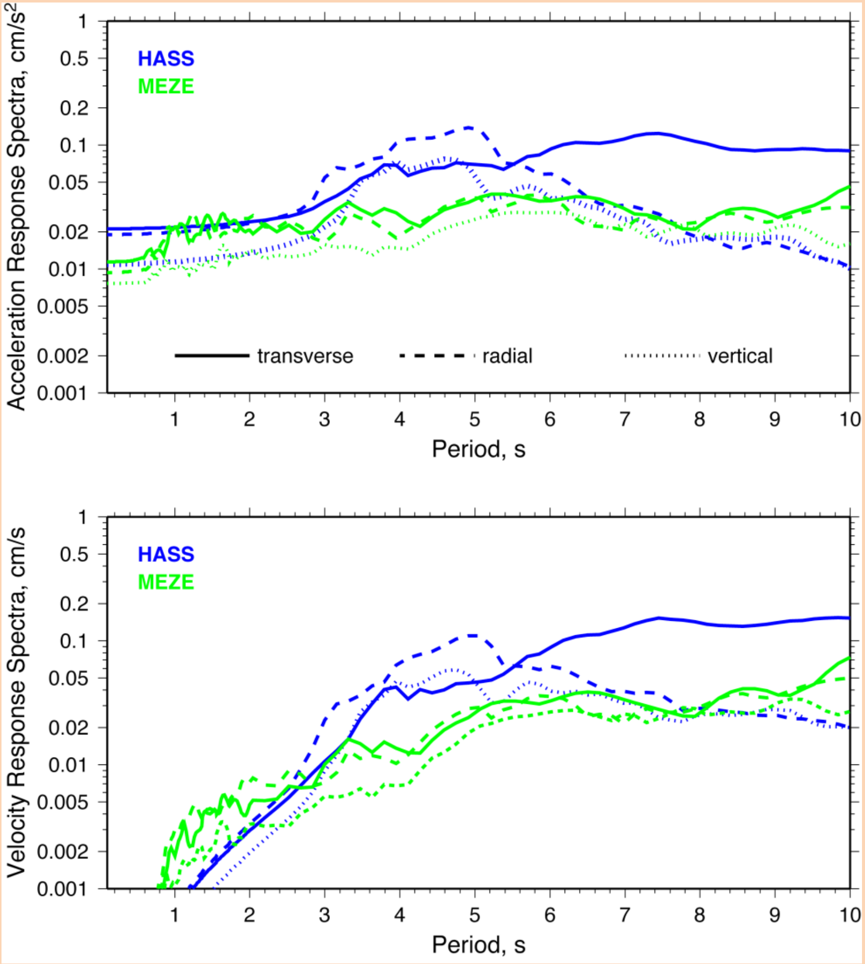
the Zagros Collisional Belt

Ground Motions in the Eastern Gulf from a Zagros Earthquake

Response Spectra

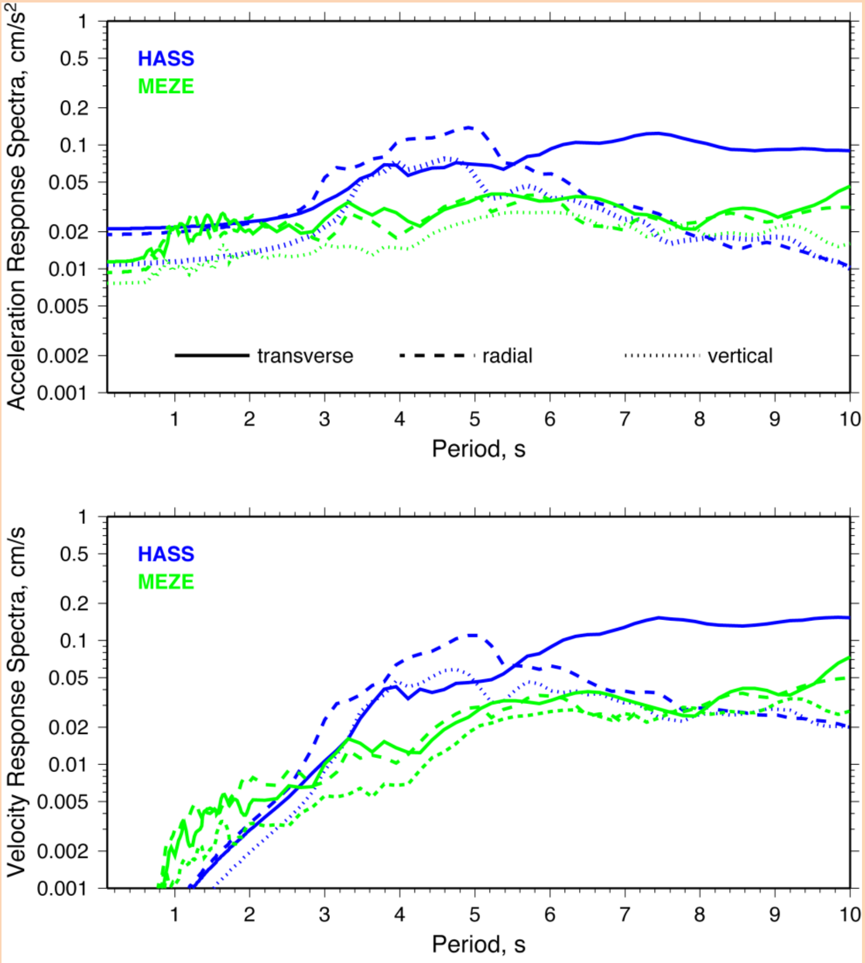
M_W 5.7 earthquake





Ground Motion Scaling

Response Spectra for M_W 5.7



0.1 cm/s² (observed spectral acc. @HASS, ~500 km, M_W 5.7)

x 10 for M_W 6.7
= **1.0 cm/s²** (… felt motions)

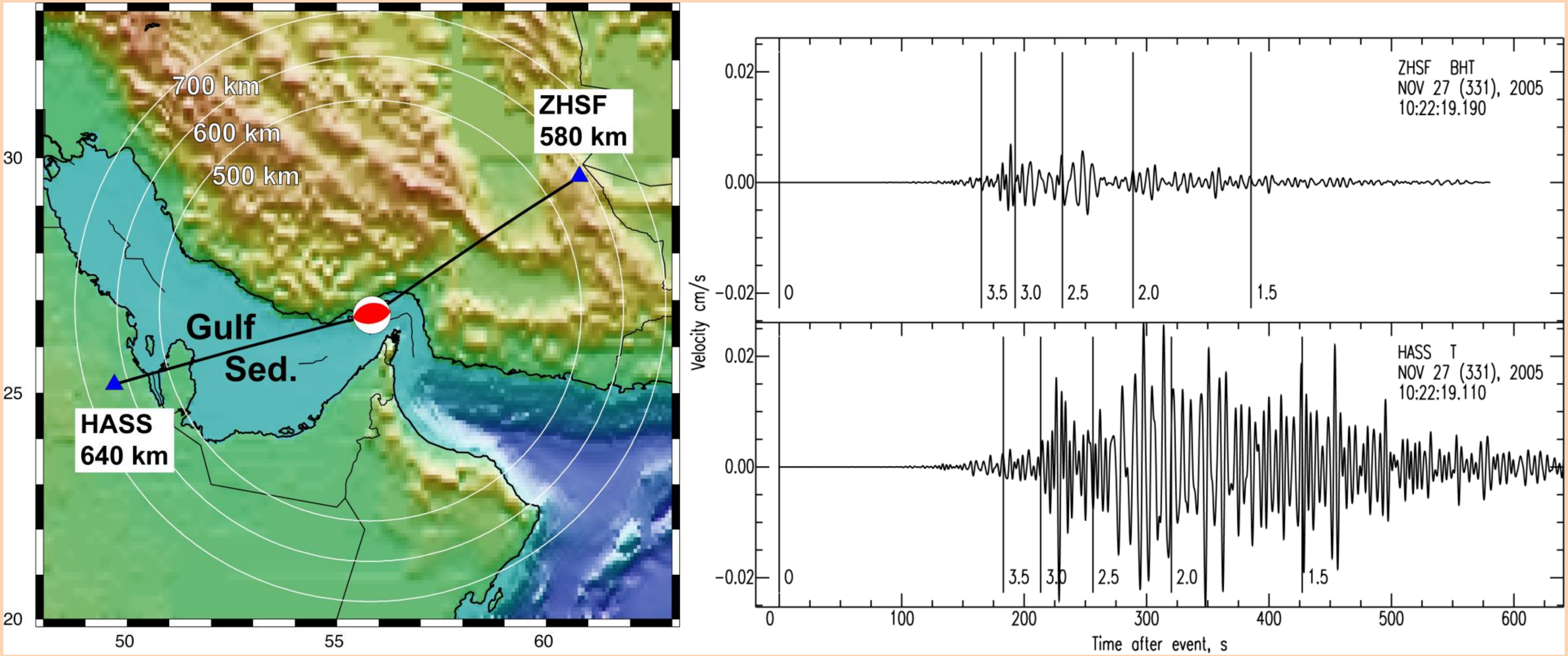
x 10 for site response
= 10.0 cm/s² ~ 1% g

x 5 for building amplification
= 50 cm/s² or ~ 5% g

Ground Motions For M_W 5.7 Earthquake Tell Us

- Larger distant earthquakes (say > M_W 6.5) can result in ground motions in the eastern Gulf
  - Felt motions at accelerations ~ 1 cm/s^2
  - Damage at higher levels
- Site response can amplify motions and result in damaging ground motions
  - Amplifications of 10 are possible in similar sedimentary geologies
- Long-period response should be of concern for large structures
  - Amplifications of 5 are possible in the building

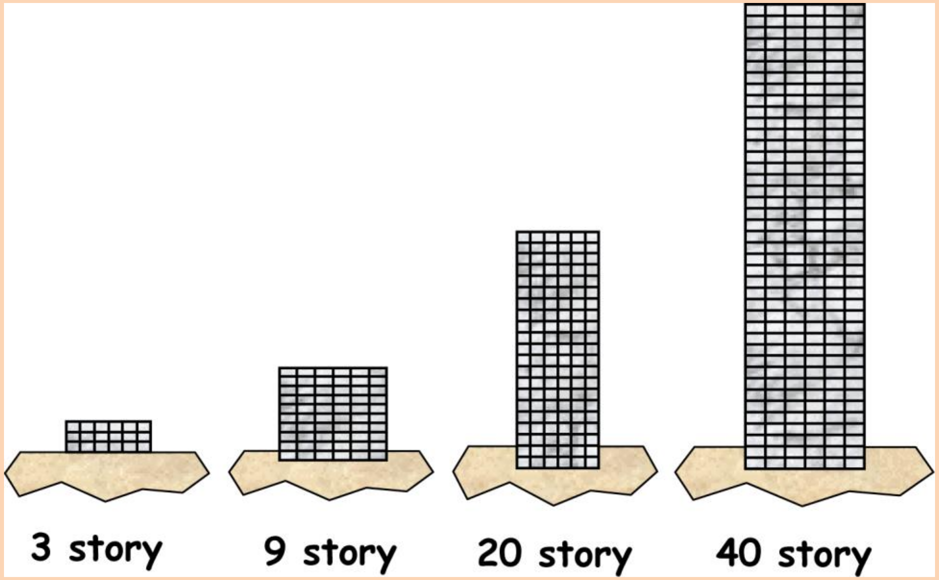
Gulf Sedimentary Structure Results in Long Duration High Amplitude Surface Waves



Nov. 27, 2005 Qeshm Island Earthquake

Earthquake Engineering: Large Structures Are Susceptible to Long-Period Motions

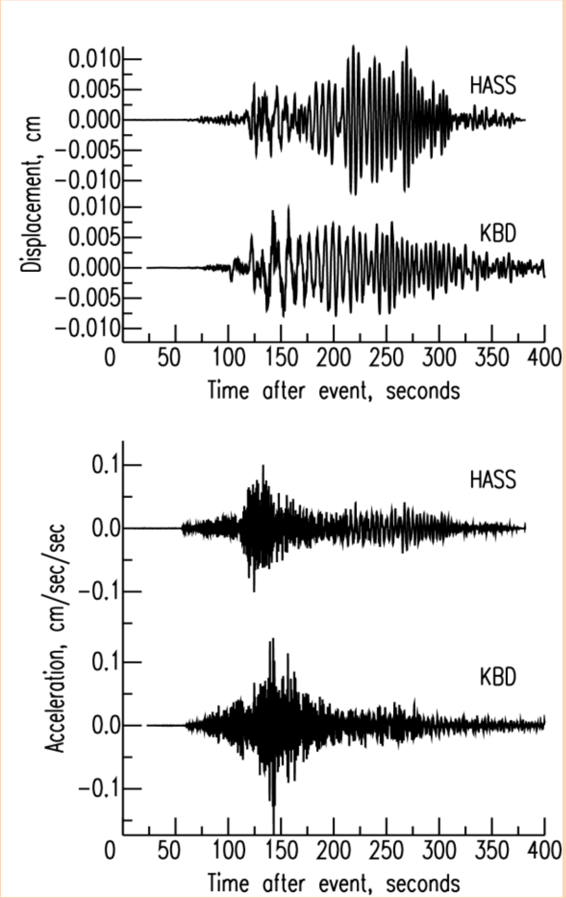
Natural (resonant) period of a building increases with building height.

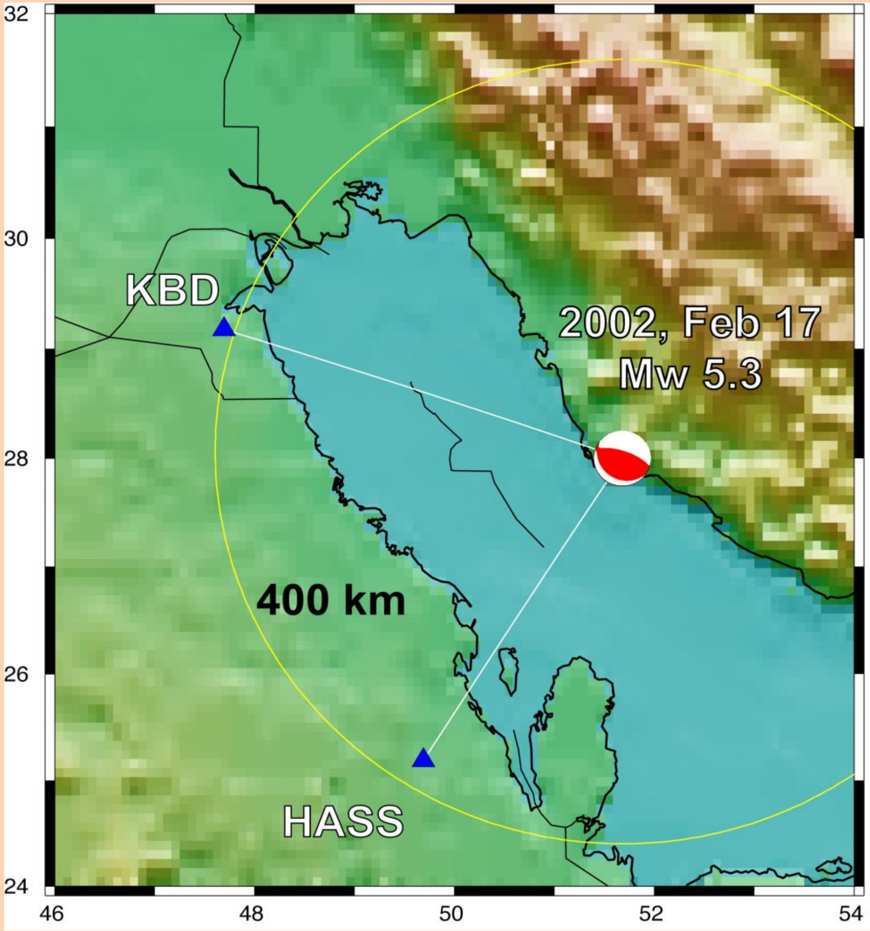


Stories	Height	Period
1	5 m	0.1 s
3	15 m	0.3 s
10	44 m	1.0 s
20	86 m	2.0 s
40	166 m	4.0 s
100	540 m	10.0 s

Actual period is typically less for than these values for tallest buildings because they are more stiff.

Consider a Moderate Earthquake M_W 5.3 and Distance ~ 400 km

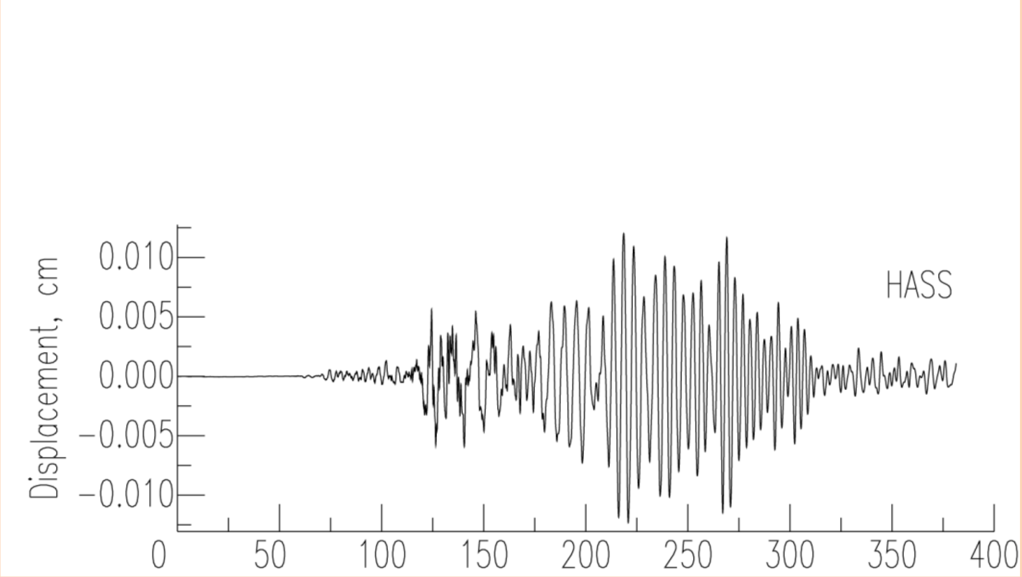




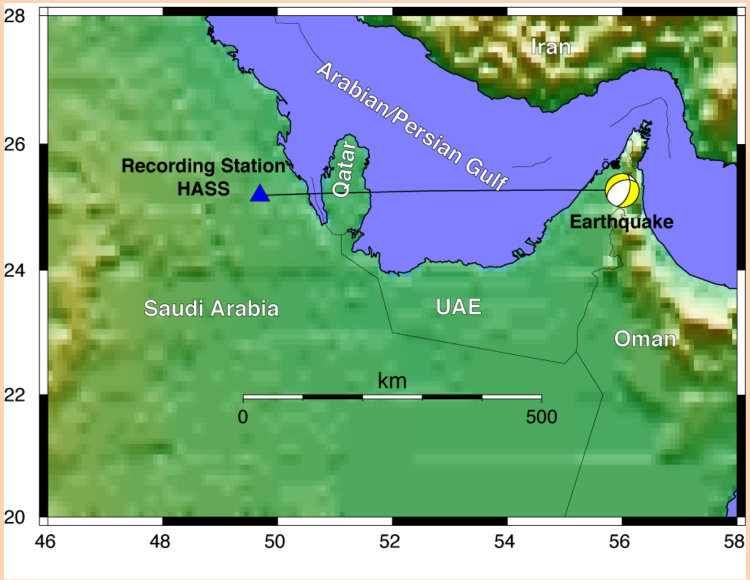
Note long-duration character

Building Response for Moderate Earthquake

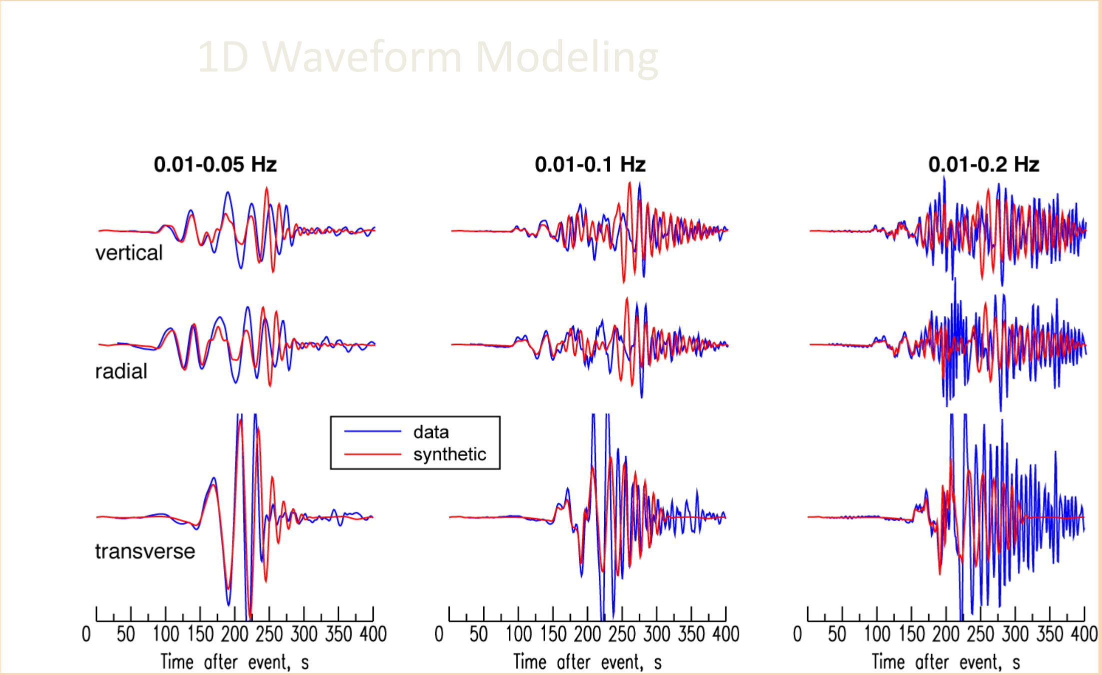
Building response computed with GEMINI
- computes modal time history
- seismic mass included
- developed at LLNL, based on SAPIV
- uni-directional acceleration & response



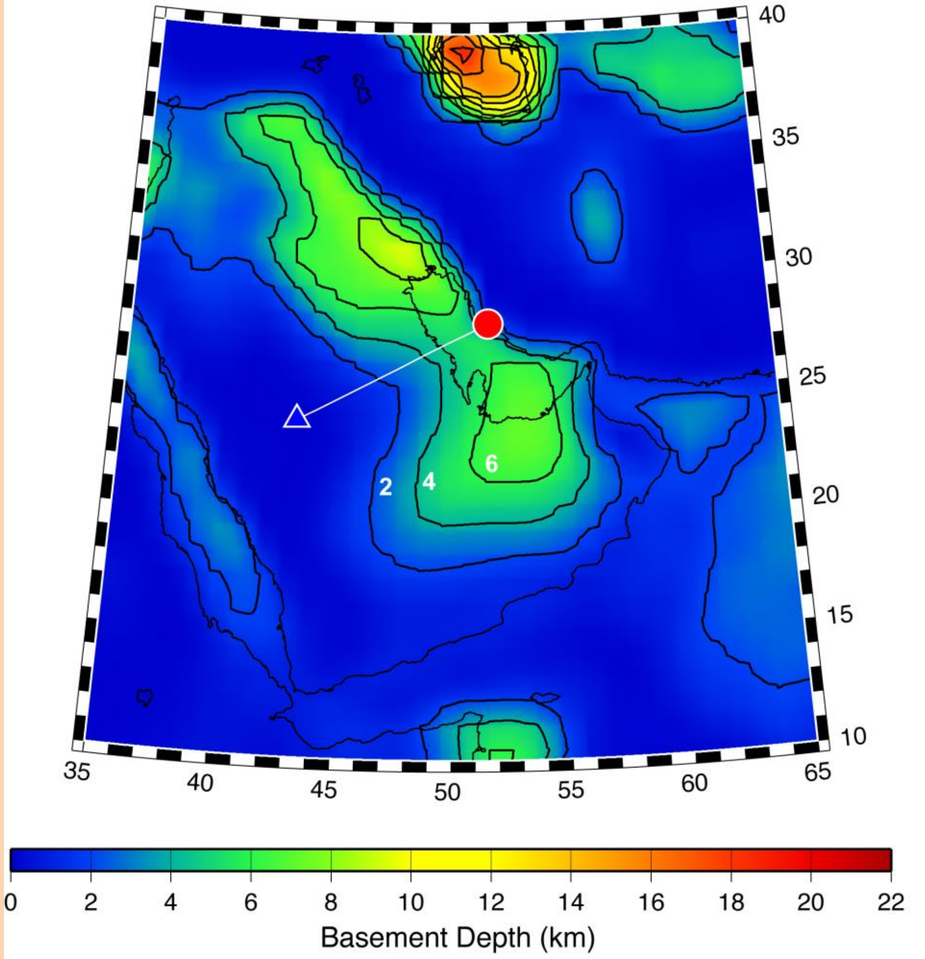
Long-Period Motions Can Be Modeled With A 1D Earth Model

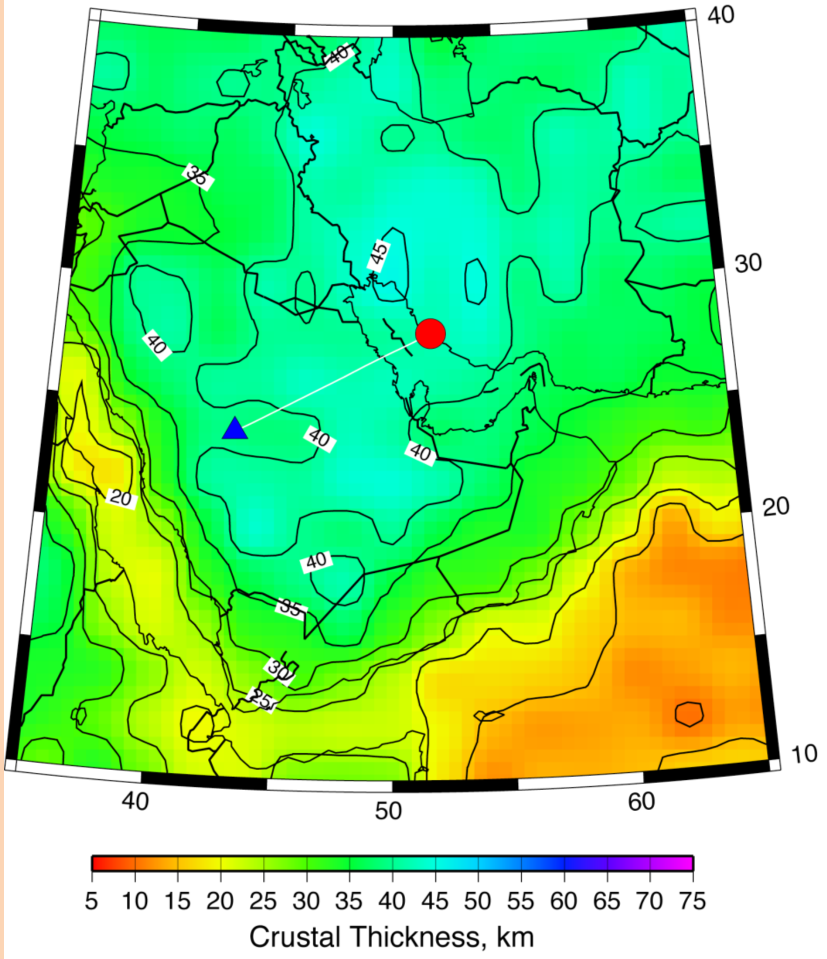


March 11, 2002 Masafi Earthquake recorded at station HASS (Al-Hasa) in Saudi Arabia



Large-Scale Models Are Available For 3D Simulations





Conclusions - 1

- Long-period ground motions from distant earthquakes in the Zagros Mountains can be large enough to impact the eastern Gulf
  - Ground motions in Iran would be destructive
  - Large buildings, bridges and structures could expect to be impacted, although damage levels must be assessed by structural engineers
  - Reclaimed land could be subject to amplification and liquefaction

Conclusions - 2

- Site response in large cities and industrial facilities needs to be investigated
  - Amplifications of 10 could be expected
- Simulations of ground motions can provide baseline for predictions from very large events
- Recommendations for future work:
  - Improved seismic velocity and density model with spatial resolution of 1-10 km
  - Must obtain geotechnical shear velocities
  - Need to include finite faulting for large earthquakes

LESSONS LEARNED FROM KAKI EARTHQUAKE

- Traditional mud-bricks buildings: Most of these buildings completely collapsed during the earthquake.
- Non-engineered buildings built of masonry or a combination of masonry and steel without any specific seismic considerations: A good majority of the non-traditional buildings in many parts of Iran are of this type and are vulnerable to earthquakes.
- Bushehr itself has been destroyed by earthquake on three occasions in recent times (1877, 1911 and 1962). It is not hard to imagine what an earthquake that destroys a nuclear power plant could do to the entire Arabian Gulf area.

LESSONS LEARNED FROM KAKI EARTHQUAKE

- Seismic design code: The implementation of the code is a major issue and in this regard effective training of professionals, providing additional guidelines for the code and effective construction control are essential.

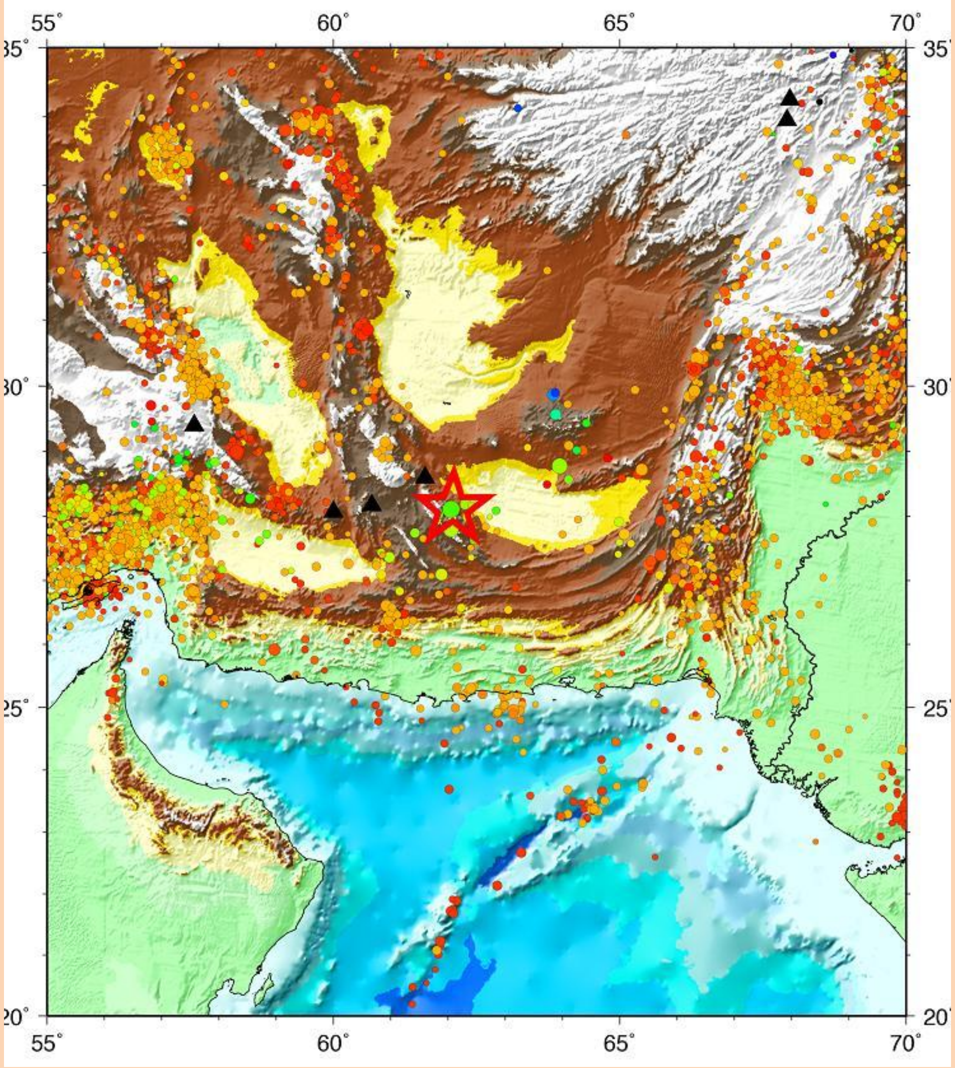
- The Arabian Gulf is a shallow body of water that consists entirely of the continental shelf. The destruction of a nuclear plant by earthquake in so shallow and narrow a water way could create a disaster many times larger than that of Chernobyl. It would affect eight littoral countries directly.

THANK YOU

www.a-alamri.com

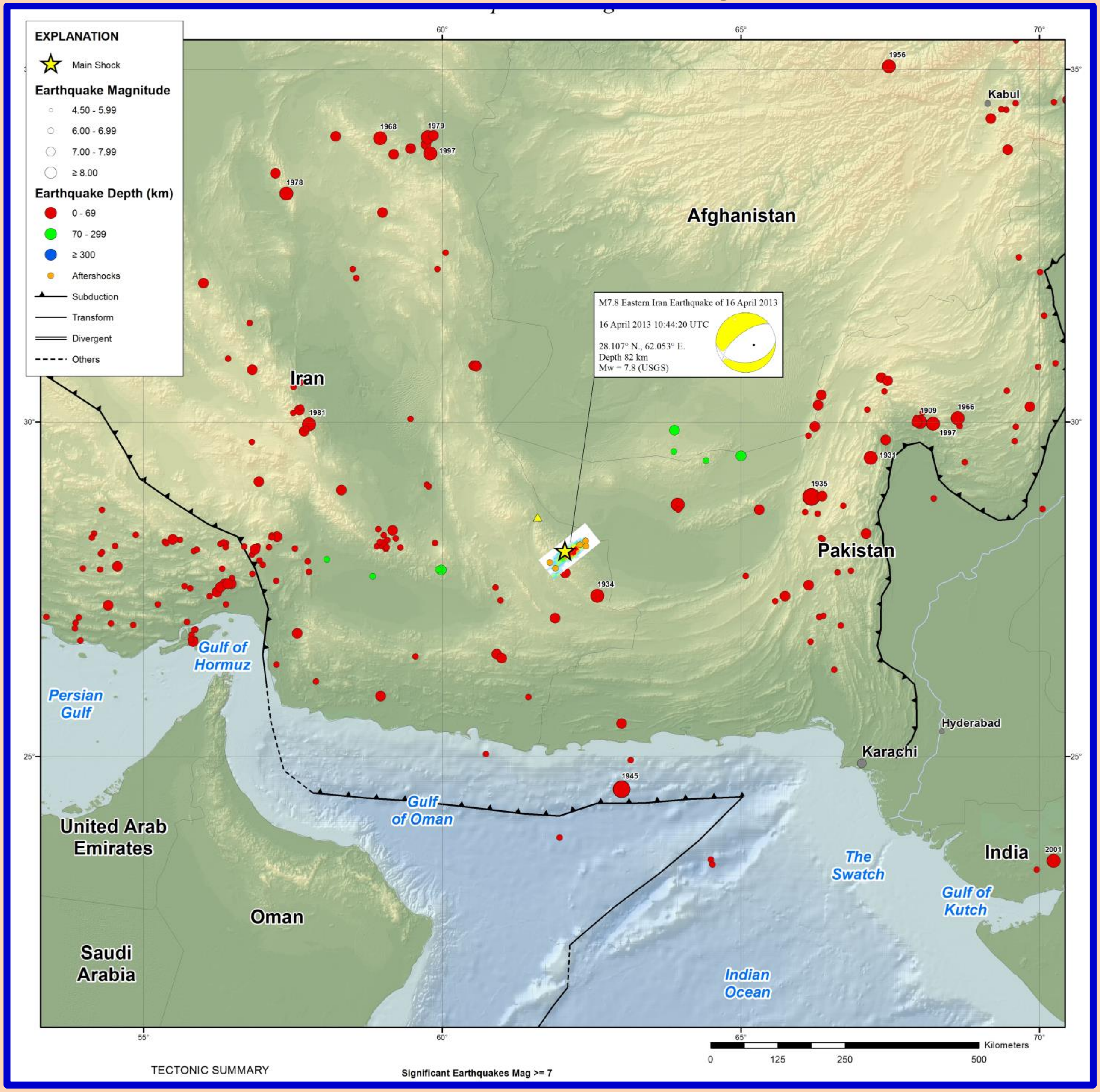
Location

- A major earthquake of magnitude 7.8 struck far east Iran near the border with Pakistan, 85 east of Khāsh, Iran on April 16th, 2013 at 10:44 UTC (15:14 Iranian time). This earthquake occurred in a sparsely populated area at a depth of 87 km.
- At least 40 people are feared dead in Iran and 38 more in Pakistanese neighboring villages.
- All communications in the area have been cut and rescue teams have been dispatched to the affected area according to the Iranian Red Crescent's.
- There were reports of tremors felt in Qatar, Bahrain, Kuwait, Abu Dhabi, in the Gulf, in Afghanistan, in Pakistan and India. In Delhi, more than 1,500 km from the epicentre, office workers evacuated buildings as fittings shook and windows rattled. Tremors lasted for around 30 seconds.



emsc-csem.org

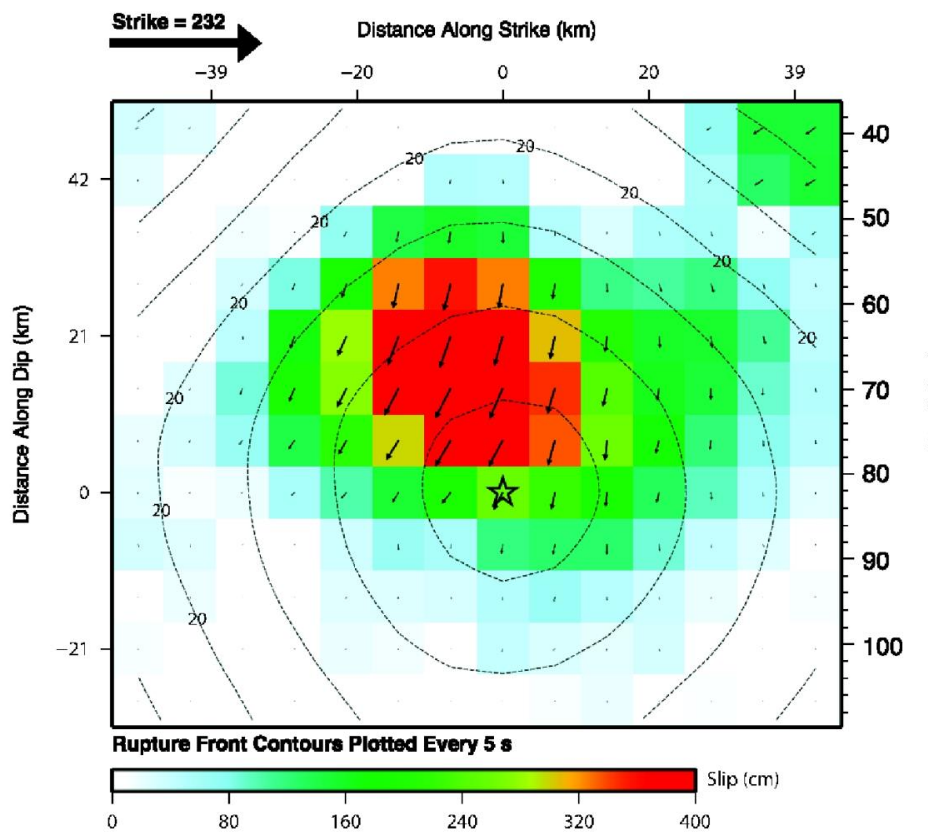
Epicentral Region



Finite Fault Model

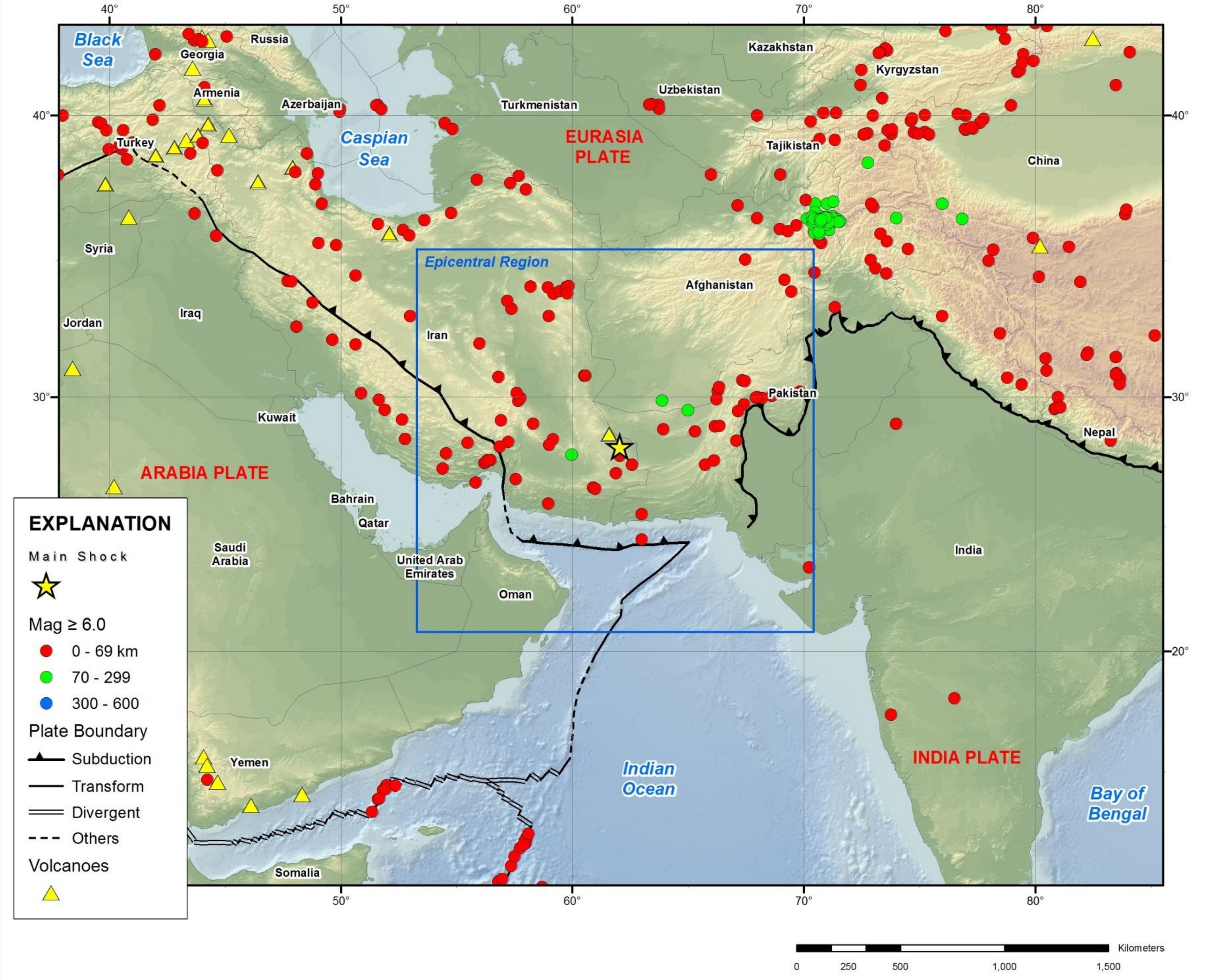
Distribution of the amplitude and direction of slip for subfault elements of the fault rupture model are determined from the inversion of teleseismic body waveforms and long period surface waves. Arrows indicate the amplitude and direction of slip (of the hanging wall with respect to the foot wall); the slip is also colored by magnitude. The view of the rupture plane is from above.

The strike of the fault rupture plane is S51W and the dip is 61 NW. The dimensions of the subfault elements are 7 km in the strike direction and 7 km in the dip direction. The rupture surface is approximately 40 km along strike and 40 km downdip. The seismic moment release based upon this plane is 4.85e+27 dyne.cm.



Tectonic Setting

- The April 16, 2013 M 7.8 earthquake east of Khash, Iran, occurred as a result of normal faulting at an intermediate depth in the Arabian plate lithosphere, approximately 80 km beneath the Earth's surface. Regional tectonics are dominated by the collisions of the Arabian and India plates with Eurasia; at the longitude of this event, the Arabian plate is converging towards the north-northeast at a rate of approximately 37 mm/yr with respect to the Eurasian plate. Arabian plate lithosphere is subducted beneath the Eurasian plate at the Makran coast of Pakistan and Iran, and becomes progressively deeper to the north.
- The subducted Arabian plate is known to be seismically active to depths of about 160 km. The frequency of moderate and large earthquakes within the subducted Arabian plate is not high compared with similar events in some other subducted plates worldwide, but several earthquakes have occurred within this slab in the region of today's event over the past 40 years, including a magnitude 6.7 shock 50 km to the south in 1983. In January of 2011, a M 7.2 earthquake occurred approximately 200 km to the east, in a similar tectonic environment to the April 16 earthquake.

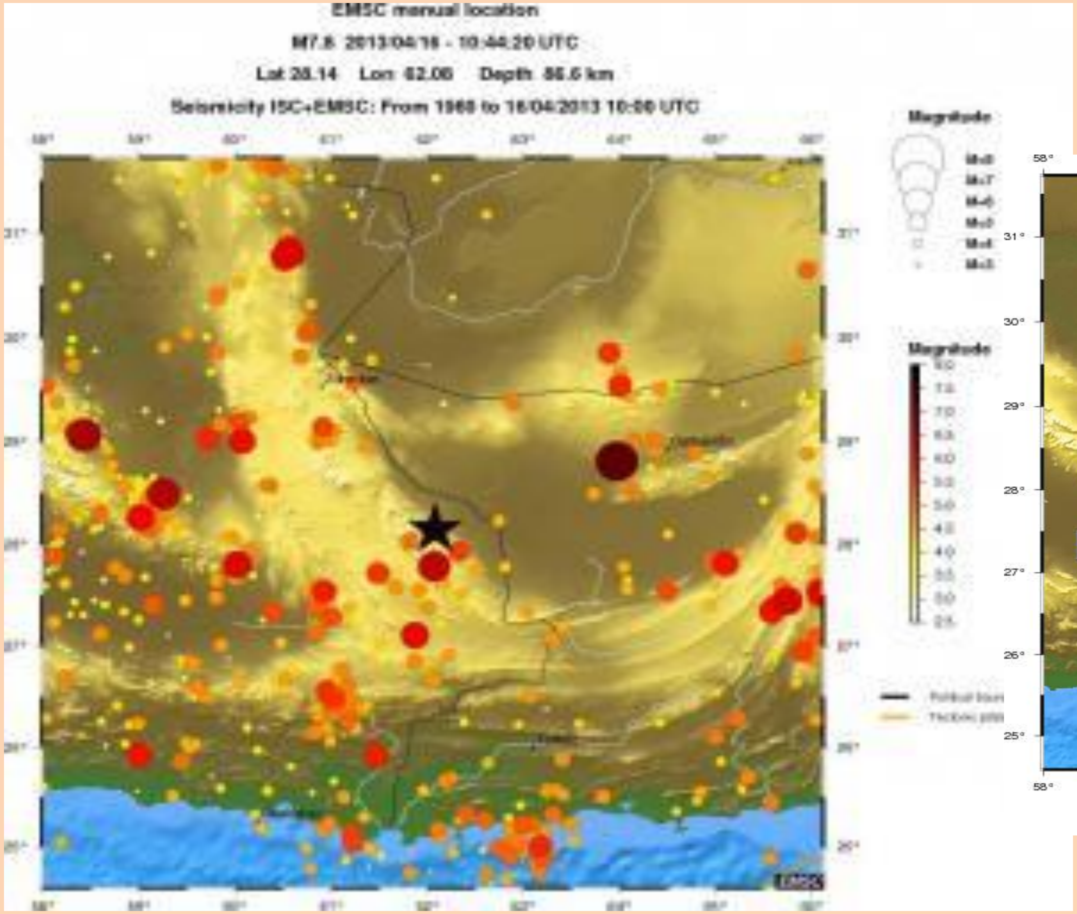


Black Sea
Russia
Georgia
Armenia
Azerbaijan
Turkey
Caspian Sea
Turkmenistan
Uzbekistan
Kazakhstan
Kyrgyzstan
Tajikistan
China
EURASIA PLATE
Syria
Iraq
Jordan
Iran
Afghanistan
Epicentral Region
Pakistan
Nepal
Kuwait
ARABIA PLATE
Bahrain
Qatar
Saudi Arabia
United Arab Emirates
Oman
India
Indian Ocean
INDIA PLATE
Bay of Bengal
Yemen
Somalia
EXPLANATION
Main Shock
Mag ≥ 6.0
0 - 69 km
70 - 299
300 - 600
Plate Boundary
Subduction
Transform
Divergent
Others
Volcanoes
Kilometers
0
250
500
1,000
1,500
40°
50°
60°
70°
80°
30°
20°

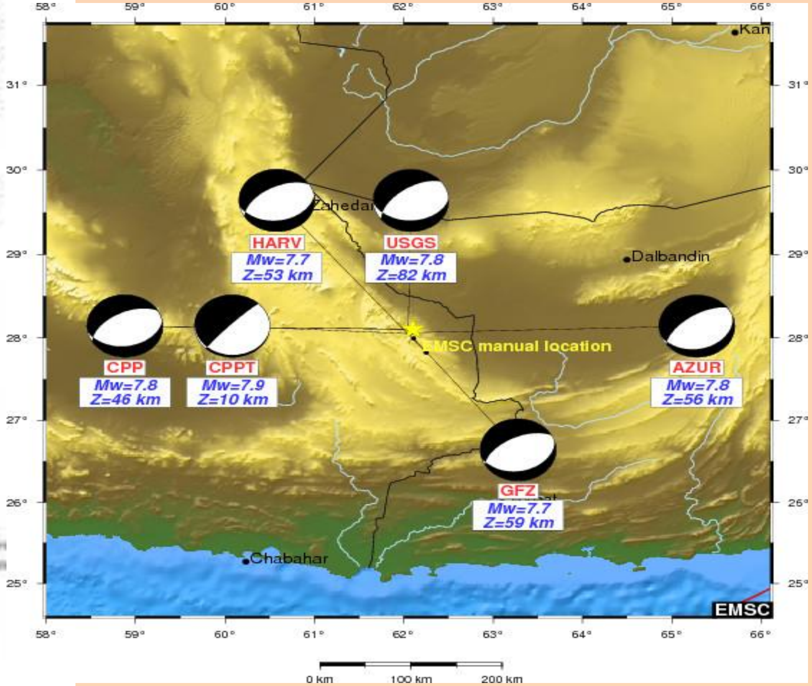
Significant Earthquakes Mag >= 7

Year	Mon	Day	Time	Lat	Long	Dep	Mag
1909	10	20	2341	30.000	68.000	0	7.0
1931	08	27	1527	29.473	67.172	35	7.1
1934	06	13	2210	27.428	62.594	35	7.0
1935	05	30	2132	28.894	66.176	35	8.1
1945	11	27	2156	24.500	63.000	0	8.0
1956	06	09	2313	35.042	67.479	35	7.6
1966	08	01	2102	30.051	68.629	9.8	7.0
1968	08	31	1047	34.045	58.960	12.3	7.2
1978	09	16	1535	33.268	57.387	15	7.4
1979	11	27	1710	34.059	59.757	8	7.1
1981	07	28	1722	29.964	57.766	13.8	7.3
1997	02	27	2108	29.970	68.220	22	7.1
1997	05	10	0757	33.833	59.796	12.8	7.2
2001	01	26	0316	23.394	70.234	16	7.7
2011	01	18	2023	28.784	63.943	68	7.2
2013	04	09	1044	28.107	62.053	82	7.8

Historical Regional Seismicity



Past Regional Seismicity as from the ISC catalogue (1964-2004) and EMSC Real Time catalogue (2005-today)



Moment Tensors Solutions

Seismotectonics of the Middle East and Vicinity

- Four major tectonic plates (Arabia, Eurasia, India, and Africa) and one smaller tectonic block (Anatolia) are responsible for seismicity and tectonics in the Middle East and surrounding region. Geologic development of the region is a consequence of a number of first-order plate tectonic processes that include subduction, large-scale transform faulting, compressional mountain building and crustal extension.
- Mountain building in northern Pakistan and Afghanistan is the result of compressional tectonics associated with collision of the India plate moving northwards at a rate of 40 mm/yr with respect to the Eurasia plate. Continental thickening of the northern and western edge of the India subcontinent has produced the highest mountains in the world, including the Himalayan, Karakoram, Pamir and Hindu Kush ranges. Earthquake activity and faulting found in this region, as well as adjacent parts of Afghanistan and India, are due to collisional plate tectonics.
- Beneath the Pamir-Hindu Kush Mountains of northern Afghanistan, earthquakes occur to depths as great as 200 km as a result of remnant lithospheric subduction. Shallower crustal earthquakes in the Pamir-Hindu Mountains occur primarily along the Main Pamir Thrust and other active Quaternary faults, which accommodate much of the region's crustal shortening. The western and eastern margins of the Main Pamir Thrust display a combination of thrust and strike-slip mechanisms.

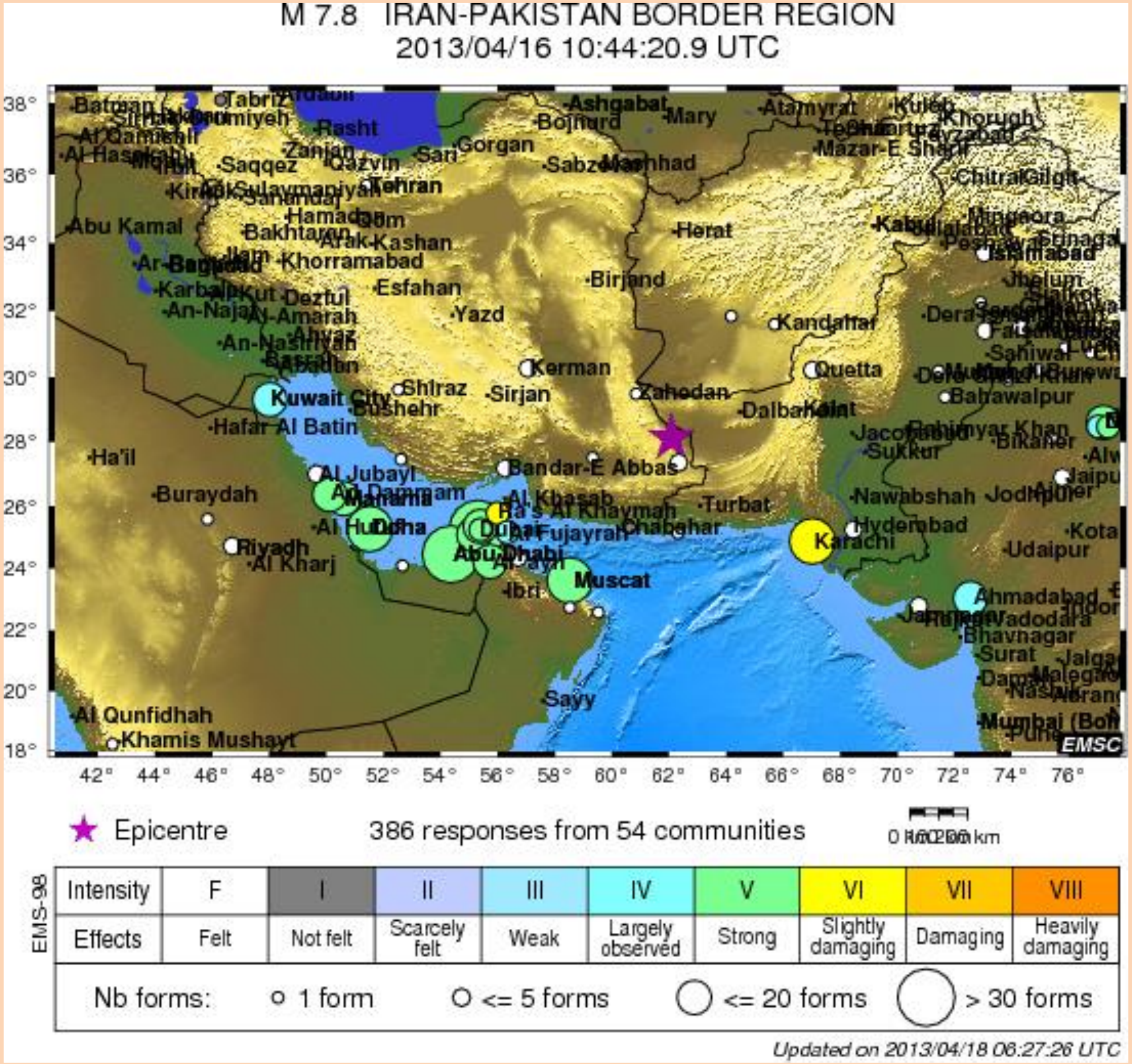
- Off the south coast of Pakistan and southeast coast of Iran, the Makran trench is the present-day surface expression of active subduction of the Arabia plate beneath the continental Eurasia plate, which converge at a rate of approximately 20 mm/yr. Although the Makran subduction zone has a relatively slow convergence rate, it has produced large devastating earthquakes and tsunamis. For example, the November 27, 1945 M8.0 mega-thrust earthquake produced a tsunami within the Gulf of Oman and Arabia Sea, killing over 4,000 people. Northwest of this active subduction zone, collision of the Arabia and Eurasia plates forms the approximately 1,500-km-long fold and thrust belt of the Zagros Mountains, which crosses the whole of western Iran and extends into northeastern Iraq. Collision of the Arabia and Eurasia plates also causes crustal shortening in the Alborz Mountains and Kopet Dag in northern Iran. Eastern Iran experiences destructive earthquakes that originate on both strike-slip and reverse faults. For example, the 16 September 1978 M7.8 earthquake, along the southwest edge of the Dasht-e-Lut Basin killed at least 15,000 people.

- Along the eastern margin of the Mediterranean region there is complex interaction between the Africa, Arabia and Eurasia plates. The Red Sea Rift is a spreading center between the Africa and Arabia plates, with a spreading rate of approximately 10mm/yr near its northern end, and 16mm/yr near its southern end (Chu, D. and Gordon, R. G., 1998).
- Seismicity rate and size of earthquakes has been relatively small along the spreading center, but the rifting process has produced a series of volcanic systems across western Saudi Arabia.

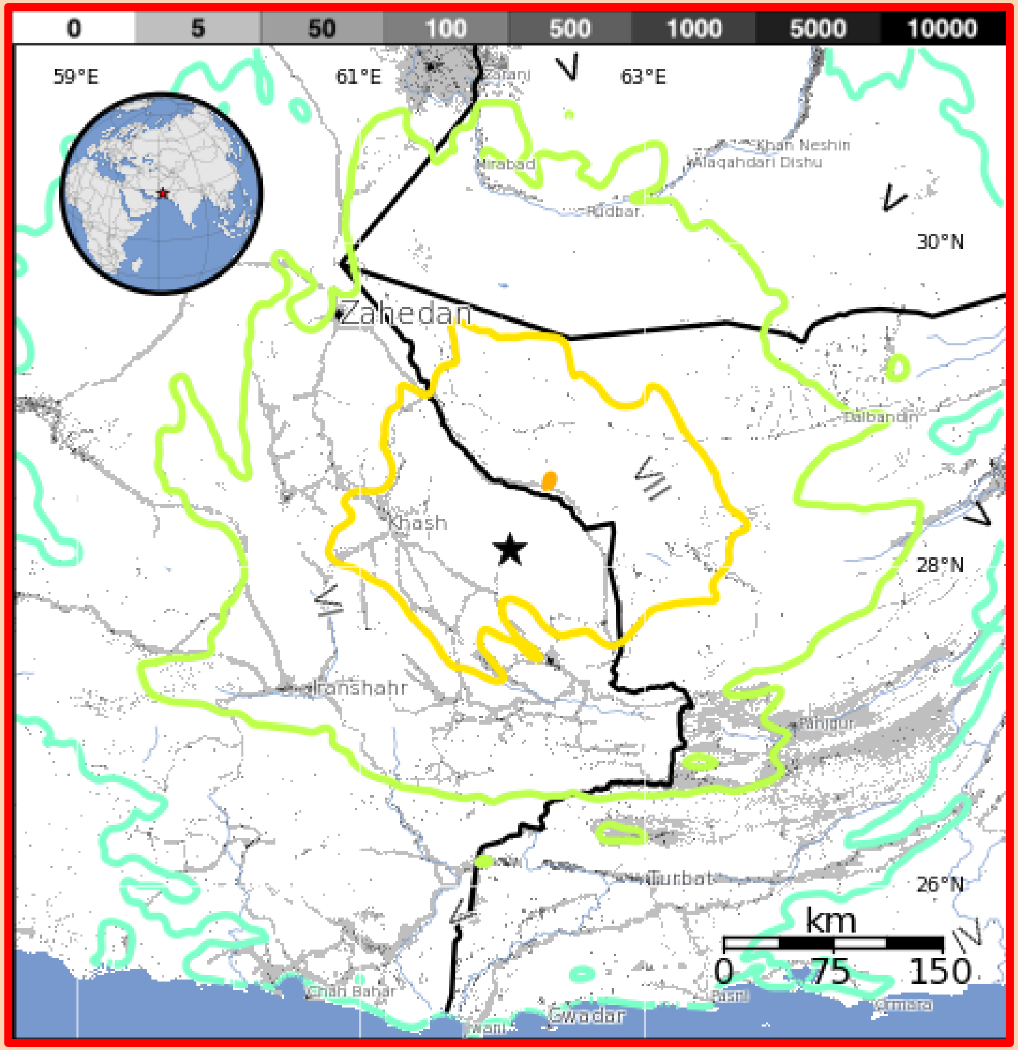
- Further north, the Red Sea Rift terminates at the southern boundary of the Dead Sea Transform Fault. The Dead Sea Transform is a strike-slip fault that accommodates differential motion between the Africa and Arabia plates. Though both the Africa plate, to the west, and the Arabia plate, to the east, are moving in a NNE direction, the Arabia plate is moving slightly faster, resulting in the left-lateral, strike-slip motion along this segment of the plate boundary. Historically, earthquake activity along the Dead Sea Transform has been a significant hazard in the densely populated Levant region (eastern Mediterranean). For example, the November 1759 Near East earthquake is thought to have killed somewhere between 2,000-20,000 people. The northern termination of the Dead Sea Transform occurs within a complex tectonic region of southeast Turkey, where interaction of the Africa and Arabia plates and the Anatolia block occurs. This involves translational motion of the Anatolia Block westwards, with a speed of approximately 25mm/yr with respect to Eurasia, in order to accommodate closure of the Mediterranean basin.

- The right-lateral, strike-slip North Anatolia Fault, in northern Turkey, accommodates much of the westwards motion between the Anatolia Block and Eurasia Plate. Between 1939 and 1999, a series of devastating M7.0+ strike-slip earthquakes propagated westwards along the North Anatolia Fault system. The westernmost of these earthquakes was the 17th August 1999, M7.6 Izmit earthquake, near the Sea of Marmara, killed approximately 17,000 people.
- At the southern edge of the Anatolia Block lies the east-west trending Cyprian Arc with associated levels of moderate seismicity. The Cyprian Arc represents the convergent boundary between the Anatolia Block to the north and the Africa Plate to the south. The boundary is thought to join the East Anatolia Fault zone in eastern Turkey; however no certain geometry or sense of relative motion along the entire boundary is widely accepted.

Intensity Distribution map



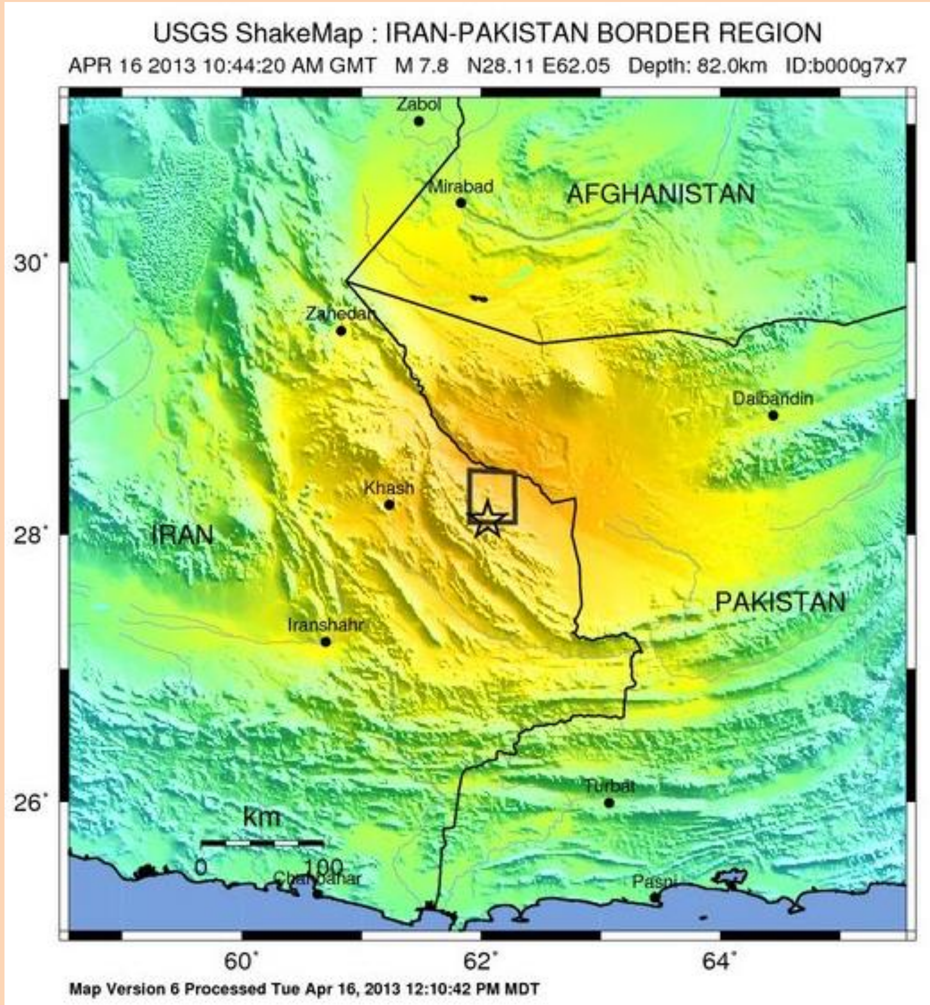
Population Exposure



MMI	City	Population
VII	Khash	70k
VI	Zahedan	552k
VI	Iranshahr	131k
VI	Rudbar	11k
VI	`Alaqahdar i Dishu	9k
VI	Mirabad	14k
V	Zaranj	0k
V	Turbat	76k
V	Zabol	122k
V	Chah Bahar	47k
IV	Gwadar	52k

where (**k = x1,000)**

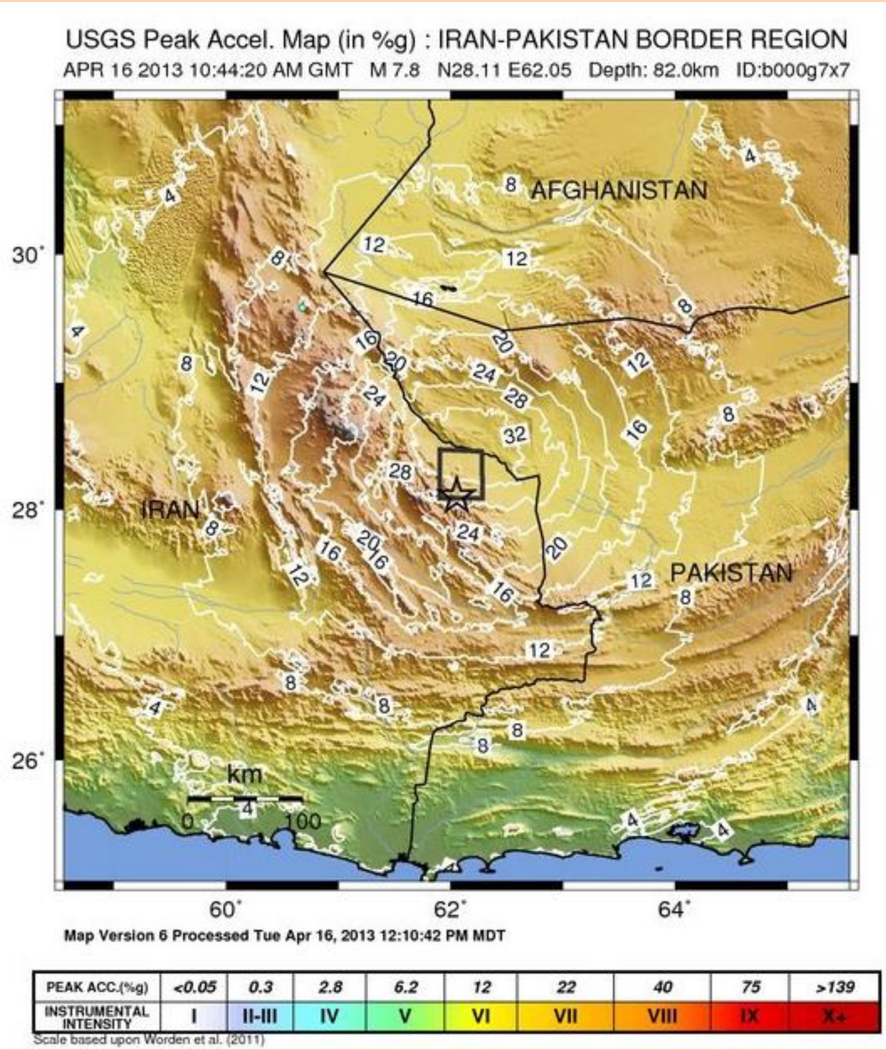
Shake map



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.02*	*0.1*	*1.4*	*4.7*	*9.6*	*20*	*41*	*86*	*>178*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

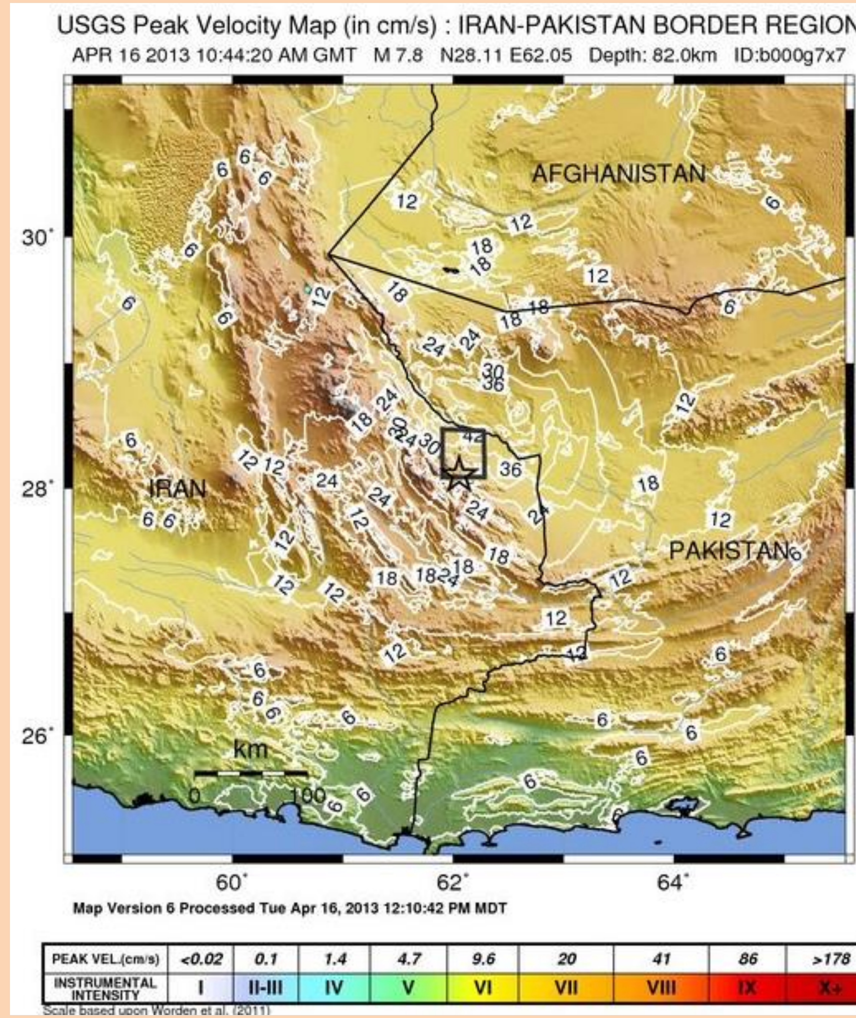
Scale based upon Worden et al. (2011)

PGA

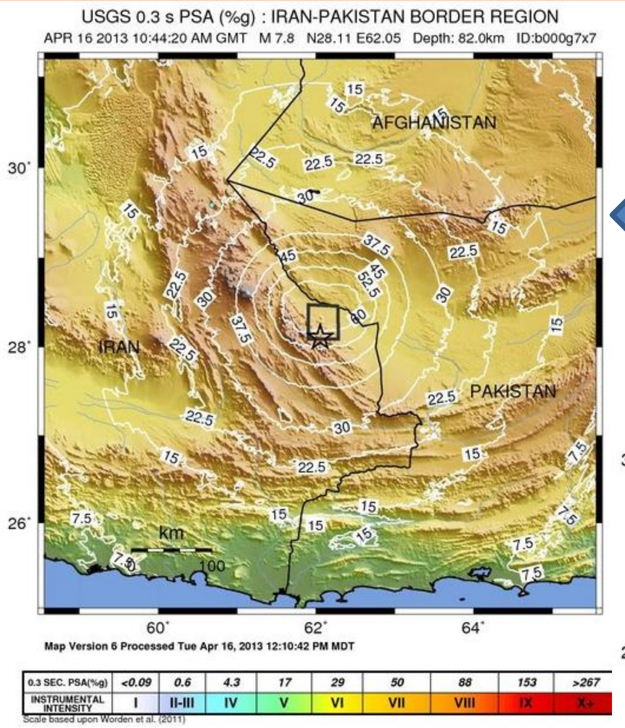


USGS Peak Accel. Map (in %g) : IRAN-PAKISTAN BORDER REGION
APR 16 2013 10:44:20 AM GMT M 7.8 N28.11 E62.05 Depth: 82.0km ID:b000g7x7
AFGHANISTAN
IRAN
PAKISTAN
km
0
100
30˚
28˚
26˚
60˚
62˚
64˚
Map Version 6 Processed Tue Apr 16, 2013 12:10:42 PM MDT
PEAK ACC.(%g) <0.05 0.3 2.8 6.2 12 22 40 75 >139
INSTRUMENTAL INTENSITY I II-III IV V VI VII VIII IX X+
Scale based upon Worden et al. (2011)

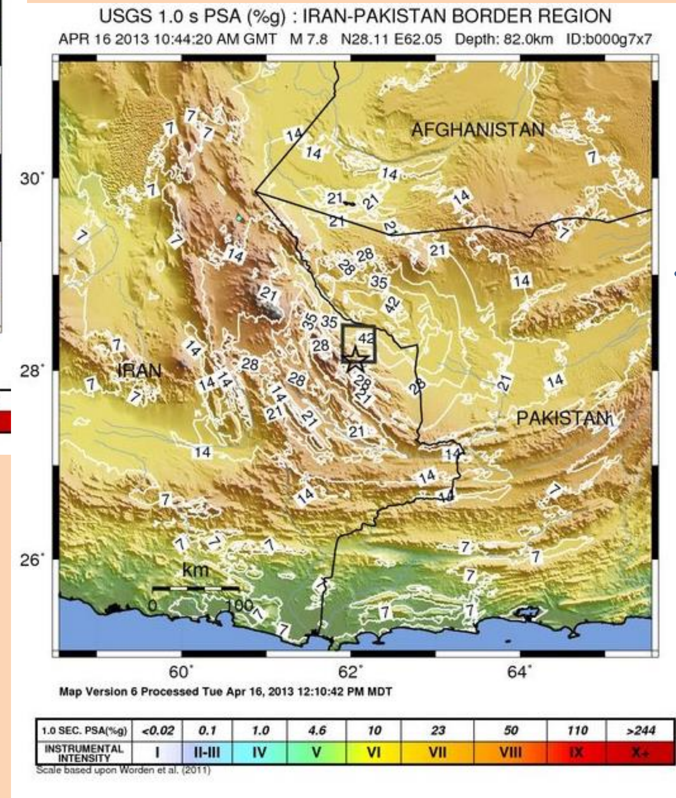
PGV



USGS Peak Velocity Map (in cm/s) : IRAN-PAKISTAN BORDER REGION
APR 16 2013 10:44:20 AM GMT M 7.8 N28.11 E62.05 Depth: 82.0km ID:b000g7x7
AFGHANISTAN
IRAN
PAKISTAN
km
0
100
30˚
28˚
26˚
60˚
62˚
64˚
Map Version 6 Processed Tue Apr 16, 2013 12:10:42 PM MDT
PEAK VEL.(cm/s) <0.02 0.1 1.4 4.7 9.6 20 41 86 >178
INSTRUMENTAL INTENSITY I II-III IV V VI VII VIII IX X+
Scale based upon Worden et al. (2011)

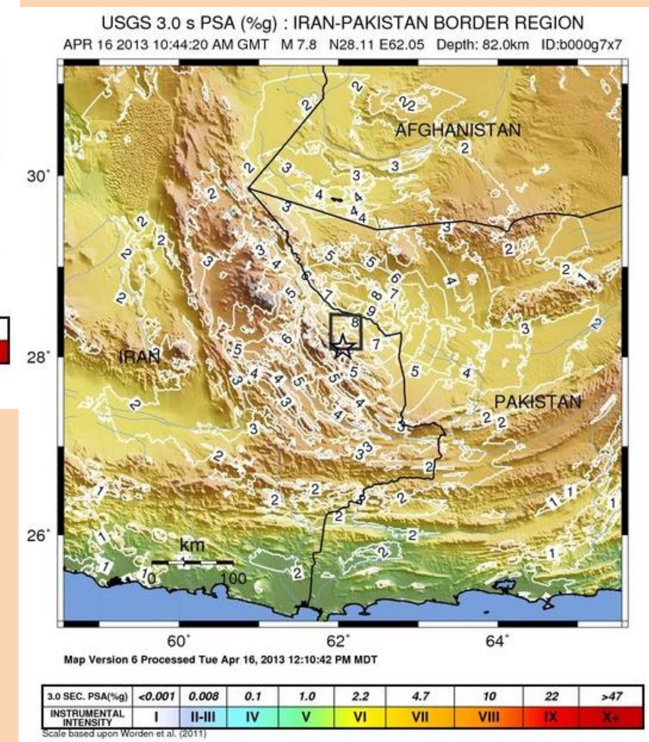


PGA (0.3s)

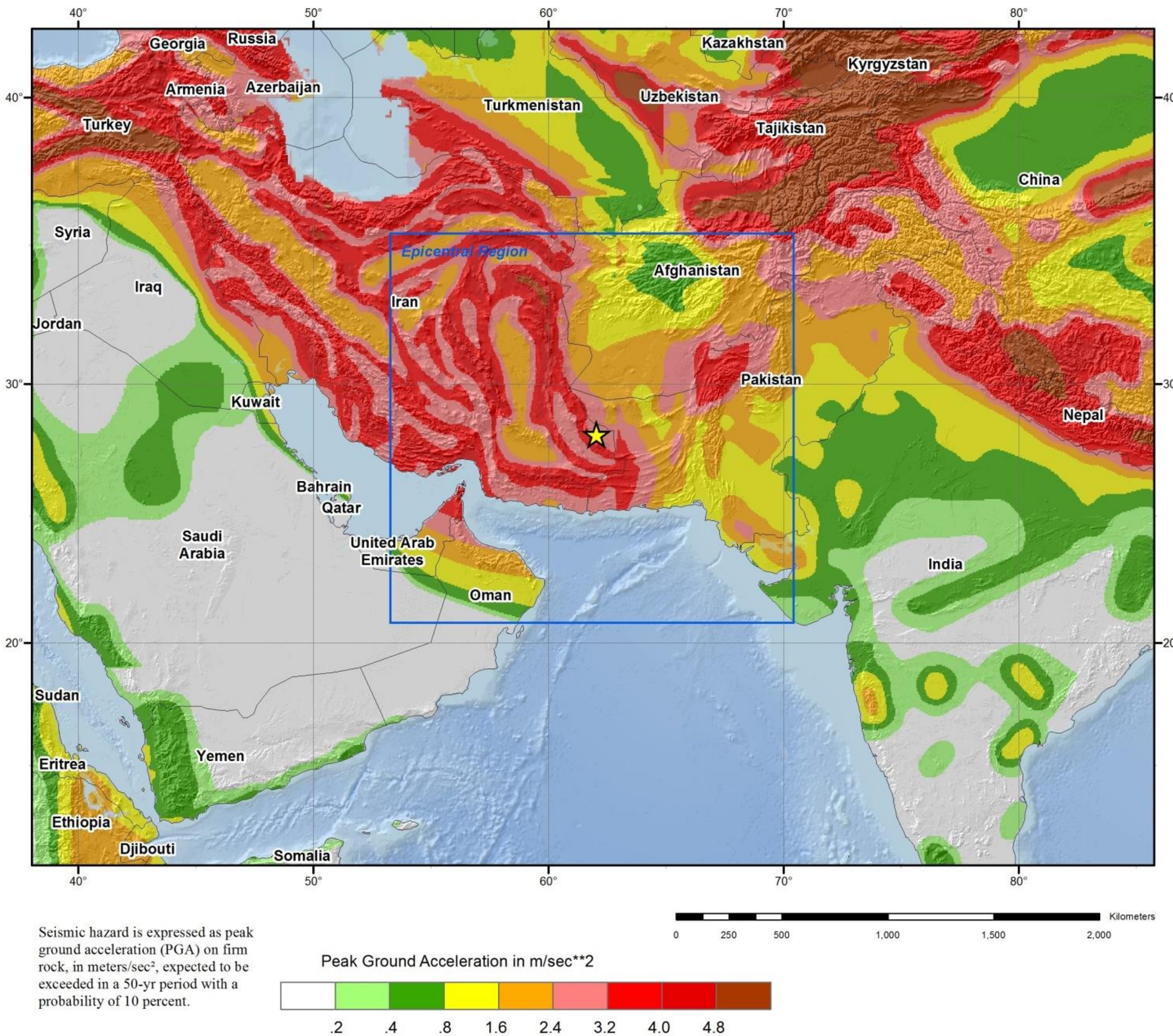


PGA (1.0s)

PGA (3.0s)



Seismic Hazard



Seismic hazard is expressed as peak ground acceleration (PGA) on firm rock, in meters/sec², expected to be exceeded in a 50-yr period with a probability of 10 percent.

Damage in Pakistan

Damage in Iran