Most earthquakes occur on either narrow plate boundaries or broad plate boundary zones

Some occur within the interior of plates
What causes continental intraplate earthquakes?
Why are they where they are?
How often do they occur?
How can we estimate the hazard?
What should we do to mitigate them?

New Madrid is spectacular example

$100M seismic retrofit of Memphis VA hospital, removing nine floors, bringing it to California standard

GENERALIZATIONS:

Continental plate interiors have number of seismic zones
Often associated with structural features (rifts, passive margins,…)
$M_{max} \sim 6.5-7.5$
Large event recurrence $>500$ yr, can be much longer
GPS shows seismicity taking up most (or all?) platewide intraplate deformation ($<1$ mm/yr)
Not clear why seismicity localized on particular features of many possible ones, or if it migrates among them
Don’t understand possible driving forces - platewide, regional (glacial rebound), local (density variations) - and thermo-mechanical structure of seismic zones

Situation comparable to understanding of plate boundary earthquakes before plate tectonics discovered
**NW EUROPE CONTINENTAL EARTHQUAKES**

Concentrated along Rhine Graben

Some similarity to New Madrid

Largest known earthquakes smaller

GPS suggests at most 1-2 mm/yr extension, not significantly different from zero

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**AUSTRALIA - CONTINENTAL INTRAPLATE EARTHQUAKES**

Relatively diffuse

May migrate between faults rather than recur

Long recurrence times for faults

GPS shows <1 mm/yr platewide deformation

$M_{\text{max}} \sim 7$ expected
HUNGARY - PANNONIAN BASIN (INTRACONTINENTAL EURASIA)

Diffuse seismicity, migrates
$M_{\text{max}}$ observed = 6.2
$M 7$ expected ~ 1000 yr from seismicity
GPS consistent - shows ~1-2 mm/yr shortening (Grenerczy et al., 2000)

2001 BHUJ INDIA EARTHQUAKE ($M_w$ 7.7)
INTRACONTINENTAL, NOT INTRAPLATE

Bhuj in broad zone of seismicity 400 km from nominal plate boundary
Bhuj within diffuse plate boundary, more like Nevada than New Madrid (2400 km away)

Stein et al., 2002
QUESTIONS (New Madrid & elsewhere):

SCIENCE (won't be resolved for 100s-1000s of years):
Is there something special about the area?
What causes large earthquakes there? Will they continue or migrate elsewhere? When did they start? How often (if ever) will they recur?

HAZARD (won't be resolved for 100s-1000s of years):
How well can we estimate the probability, size, and shaking of future earthquakes? How uncertain are the results?

POLICY (immediate):
Should earthquake provisions in present building code immediately be upgraded to California-level?

NEW MADRID SEISMIC ZONE (NMSZ)
Type example of continental intraplate seismicity
Most active in North American continental interior
Seismicity 1/30-1/100 California rate, owing to difference in motion rates

M>5 ~ every 15 yr
M>6 ~ every 150 yr
M>7 in 1811-12
MODIFIED MERCALLI INTENSITY SCALE

Macroscopic measure of shaking
Estimated for historic earthquakes from accounts of what happened
Plot isoseismals - intensity contours

I. Shaking not felt, no damage. Not felt except by a very few under especially favorable circumstances.

II. Shaking weak, no damage: Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration like passing of truck. Duration estimated.

IV. Shaking light, no damage: During the day felt indoors by many, outdoors by very few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing automobiles rocked noticeably. (0.015g-0.02g)

V. Shaking moderate, very light damage: Felt by nearly everyone, many awakened. Some dishes, windows, and so on broken; cracked plaster in a few places; unstable objects overturned. Disturbances of trees and poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (0.03g-0.04g)

VI. Shaking strong, light damage: Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster and damaged chimneys. Damage slight. (0.06g-0.07g)

VII. Shaking very strong, moderate damage: Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving cars. (0.10g-0.15g)

VIII. Shaking severe, moderate to heavy damage: Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving cars disturbed. (0.25g-0.30g)

IX. Shaking violent, heavy damage: Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (0.50g-0.55g)

X. Shaking extreme, very heavy damage: Some well-build wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed, slopped over banks. (More than 0.60g)


XII. Damage total. Waves seen on ground surfaces. Lines of sight and level destroyed. Objects thrown into the air.

Largest 1811-1812 earthquakes caused log cabin collapse at New Madrid; minor damage in St Louis, Nashville, Louisville, etc.

Previously interpreted as implying M8 (Johnston, 1996), instead imply low-mid M7 (Hough et al., 2000)

M 7.2 fits observed building damage better (Kochkin & Crandell, 2004)
EARTHQUAKE HISTORY
Paleoseismology - in this area primarily paleoliquefaction - shows events
~ 1450 and 900 AD

Sand blows in New Madrid area (USGS)

SEISMICITY CONSTRAINTS ON LARGE EARTHQUAKE MAGNITUDE & RECURRENCE
Previously interpreted as 550-1100 yr recurrence for Ms > 8.3 (Johnston and Nava, 1985)
This recurrence is actually for M > 7
If large earthquakes occur every 500-1000 yr, they're low M 7

New Madrid Seismic Zone
Frequency-Magnitude Relationship

Newman et al, 1999
NEW MADRID SEISMIC ZONE
OBSERVATIONS w/o PARADIGM

Associated with ancient failed Reelfoot rift

GPS indicates seismicity taking up most (or all?) platewide intraplate deformation (<1 mm/yr)

Not clear why seismicity localized here rather than other fossil features

May have become active (for some reason) within past few Ma or less.

Unclear how long it will last

Braile et al., 1986
Geodetic, Geological, & Earthquake history don’t agree

“How wonderful that we have met with a paradox. Now we have some hope of making progress.” — Niels Bohr

OLD VIEW:
Intraplate zone acts like slow (< 2 mm/yr) plate boundary
Steady focused deformation: past shown by geology & earthquake record consistent with present shown by geodesy, and predicts future seismicity

NEW VIEW:
Complex regional system of interacting faults
Deformation varies in space and time
Deformation can be steady for a while then shift
Past can be poor predictor

McKenna, Stein & Stein, 2007
We started GPS at New Madrid expecting to find strain accumulating, consistent with M7+ events ~500 years apart

After 8 years, 3 campaigns, 70 people from 9 institutions ...

1999 surprise: no motion: 0 +/- 2 mm/yr

2 Centuries Later, Good News for Quake Area, Maybe


Midwesterners who worry about earthquakes got some good news last week: their risk of catastrophe may have been vastly overstated.

New measurements taken around New Madrid, MO - the epicenter of devastating earthquakes in 1811 and 1812 - show that the ground there is scarcely moving. According to many scientists, this means that it will take 2,500 to 10,000 years before another very large earthquake could occur in the region, although smaller, less damaging earthquakes are possible.

"The motions are small to zero," said Dr. Seth Stein, a professor of geological sciences at Northwestern University in Evanston, Ill., who made the new measurements. Earlier evidence showing rapid regional ground motion, a geologic sign that large quakes are probable, "was based on honest scientific errors," Dr. Stein said.
Rate $v$ of motion of a monument that started at $x_1$ and reaches $x_2$ in time $T$

$$v = \frac{x_1 - x_2}{T}$$

If position uncertainty is given by standard deviation $\sigma$

Rate uncertainty is

$$\sigma_v = 2^{1/2} \frac{\sigma}{T}$$

Rate precision improves with longer observations

Rates $<$ 0.2 mm/yr, will continue to converge on zero unless ground motion starts

Strain rate does the same:

$< 2 \times 10^{-9}$ /yr and shrinking

Calais & Stein, 2009
GPS SHOWS LITTLE OR NO MOTION

Motions with respect to the rigid North American plate are < 0.2 mm/yr, and within their error ellipses. Data do not require motion, and restrict any motion to being very slow.

Very long time would be needed to store up the slip needed for a future large earthquake
For steady motion, M 7 is at least 10,000 years away: M 8 100,000

Seismicity migrates among faults due to fault interactions
Many faults active in past show little present seismicity

Large earthquake cluster in past 2000 years isn’t representative of long term NMSZ behavior
This cluster may be ending

Calais & Stein, 2009

Stein 2007
Calais & Stein, 2009
Tuttle (2009)
GEOLOGY IMPLIES NEW MADRID EARTHQUAKES ARE EPISODIC & CLUSTERED

The absence of significant fault topography, the jagged fault, and other geological data, imply that the recent pulse of activity is only a few thousand years old.

New Madrid earthquake history inferred from Mississippi river channels

Holbrook et al., 2006

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<th>Holocene Punctuated Slip</th>
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Portageville Cycle | Reelfoot Cycle | New Madrid Cycle

NEW MADRID SEISMICITY: 1811-12 AFTERSHOCKS?

Ongoing seismicity looks like aftershocks of 1811-12, as suggested by the fact that the rate & size are decreasing. Moreover, the largest are at the ends of the presumed 1811-12 ruptures

Stein & Newman, 2004
In Dieterich (1994) friction model aftershock duration \( t_a \propto 1/\text{stressing rate} \)

For simple geometry \( t_a = A \sigma \pi w / \mu v \)

A fault friction parameter \( \sigma \) normal stress \( w \) fault vertical extent \( \mu \) rigidity \( v \) velocity across fault

Current seismicity likely to be largely aftershocks rather than implying location of future large events

LONG INTRAPLATE AFTERSHOCK SEQUENCES EXPECTED IN SLOWLY DEFORMING REGIONS

CONTINENTAL INTRAPLATE EARTHQUAKES ARE OFTEN EPISODIC, CLUSTERED & MIGRATING

“Large continental interior earthquakes reactivate ancient faults ... geological studies indicate that earthquakes on these faults tend to be temporally clustered and that recurrence intervals are on the order of tens of thousands of years or more.” (Crone et al., 2003)

Stein & Liu, 2009

Meers fault, Oklahoma Active 1000 years ago, dead now
During the past 700 years, destructive earthquakes generally occurred in different locations, indicating a migration of seismicity with time. (Camelbeeck et al., 2007)

In a few hundred years, earthquakes appear to be clusters scattered in the region. In few thousand years, clusters connect and form belts. In tens of thousands of years, earthquakes are scattered in the whole region.
Effect of major (5 MPa) weak zones

Complex space-time variability due to fault interactions

Seismicity extends beyond weak zones

Short-term seismicity does not fully reflect long-term

Variability results from steady platewide loading without local or time-variable loading

Li, Liu & Stein, 2009

HOW TO GET TEMPORAL CLUSTERS

1 - Because of slow loading, repeated earthquakes (clusters) occur if fault strength decreases (for unknown reasons).

Earthquakes (1MPa stress drop) repeatedly occur in a 500-700 year period if there is a continuous strength decline (0.5 MPa /500 years). Without this decline no repeated earthquakes occur.

Li, Liu & Stein, 2009
HOW TO GET TEMPORAL CLUSTERS

2 - Nearby faults fail by stress transfer, causing apparent cluster possibly hard to resolve with geologic data

Tuttle (2009)

GPS DATA SHOW NORTH AMERICAN PLATE STABLE TO BETTER THAN 1 MM/YR, AS MEASURED BY MISFITS TO EULER VECTOR PREDICTIONS

Corresponds to M 7 about every 1000 yrs, if all deformation released seismically - as seems the case

Stein & Sella, 2002
GPS SHOW INTRAPLATE DEFORMATION DOMINATED BY GLACIAL ISOSTATIC ADJUSTMENT (GIA)

Clear pattern of positive velocities in and around Hudson Bay that decreases going southwards to zero (hinge line), beyond which velocities are initially negative and then rise to near zero.

Detecting GIA Using GPS

Large vertical signal observed ~10 mm/yr

GPS vertical velocities with respect to ITRF2000
GPS SHOW INTRAPLATE DEFORMATION DOMINATED BY GLACIAL ISOSTATIC ADJUSTMENT (GIA)

GIA & INTRAPLATE EARTHQUAKES?

GIA may cause some intraplate earthquakes:

Stein et al [1979] - coasts of Atlantic Canada, NE US
Stein et al [1989] - other glaciated coasts (Greenland, Beaufort Sea, Norway)
James & Bent [1994]; Wu & Johnston [2000] - St. Lawrence Valley
Grollimund and Zoback [2001] – New Madrid

GIA data will show how significant an effect this might be

Tsunami damage from 1929 Grand Banks, Newfoundland M 7.2 (27 deaths)
EARTHQUAKES OCCUR ON OTHER PASSIVE CONTINENTAL MARGINS

Predicted hazard from historic seismicity is highly variable
Likely overestimated near recent earthquakes, underestimated elsewhere
More uniform hazard seems more plausible - or opposite if time dependence considered
Map changes after major earthquakes

SHORT RECORD OF SEISMICITY & HAZARD ESTIMATE

Africa-Eurasia convergence rate varies smoothly

Stein et al., 1989

Argus et al., 1989
SHORT RECORD OF SEISMICITY & HAZARD ESTIMATE

Africa-Eurasia convergence rate varies smoothly

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HUNGARY: ALTERNATIVE HAZARD MAPS

Peak Ground Acceleration
10% probability of exceedance in 50 years

Historic seismicity

Toth et al., 2004
EASTERN US versus CANADA: ALTERNATIVE HAZARD MAPS

Historic seismicity

Halchuk and Adams, 1999

Diffuse Hazard

IS NEW MADRID AS HAZARDOUS AS CALIFORNIA?

Frankel et al., 1996

Proposed new building code would require California standards
HOW WELL CAN NMSZ HAZARD BE ASSESSED?

"GAME OF CHANCE OF WHICH WE STILL DON'T KNOW ALL THE RULES" (Lomnitz, 1989)

- Earthquake causes unclear, so no a priori recurrence information
- Magnitudes and recurrence intervals difficult to infer
- Ground motion ill-constrained since no large earthquakes here since seismometer invented (~1900)

Can make range of estimates, including Frankel et al. map’s of NMSZ hazard comparable to San Francisco or Los Angeles.

High hazard estimate results from three assumptions:

1) Large earthquakes will be M 8, larger than the low M 7 recently found for 1811-12
2) Ground motion will significantly exceed that predicted by previous models
3) Hazard for building code defined as maximum predicted shaking every 2500 years (2% probability in 50 yr)

EFFECTS OF ASSUMED GROUND MOTION MODEL

Effect as large as one magnitude unit

Frankel model, developed for maps, predicts significantly greater shaking for M >7

Frankel M 7 similar to other models’ M 8

Frankel & Toro models averaged in 1996 maps; Atkinson & Boore not used

Newman et al., 2001
UNCERTAINTIES IN NMSZ HAZARD MAPS

Areas of predicted significant hazard differ significantly, depending on poorly known parameters.

Assumed $M_{\text{max}}$ on main fault has largest effect near fault.

Assumed ground motion model has regional effect, because it also influences predicted hazard from earthquakes off main fault.

Differences have major policy implications (e.g. Memphis & St. Louis).

Newman et al., 2001

EXPECTED HAZARD: CALIFORNIA AND NMSZ EARTHQUAKES

NMSZ quakes of given magnitude 30-100 times less common than in California

Shaking from NMSZ quakes comparable to that from California quakes one magnitude larger

Net effect: expect annual NMSZ hazard 1/3-1/10 that of California
ASSUMED HAZARD DEPENDS ON TIME WINDOW

Over 100 years, California site much more likely to be shaken strongly than NMSZ one

Over 1000 years, some NMSZ sites shaken strongly a few times; many in California shaken many times

Short time relevant for buildings with 50-100 yr life

EFFECT OF 2500 YEAR CRITERION - MUCH LONGER THAN BUILDING LIFE

Risk of major damage to typical building during 50 yr life much lower in NMSZ than California

Proposed new code (IBC2000) defines hazard as maximum shaking in 2500 yr (2% probability in 50 yr)

2500 yr predictions larger and more uncertain than over 500 yr (10% probability in 50 yr) used previously, in Europe, and for other natural hazards (floods, etc).

IBC 2000 code does not use 2500 yr throughout California, because in some places predicted shaking was so high as to require significant strengthening over present codes

Don’t know if/where 2500 yr criterion is cost-effective
FEMA BUILDING RISK COMPARISON

FEMA uses Frankel et al. map hazard estimates (high end of possible values) to estimate annual earthquake loss ratio (AELR), ratio of annualized earthquake loss to the replacement cost of all buildings in the area.

Values for Memphis and St. Louis are about 1/5 - 1/10 of those for San Francisco and Los Angeles. Memphis ranks 32nd among major U.S. cities; St. Louis ranks 34th.

Since ratios are equivalent to the fractional risk of building damage, estimate predicts NMSZ buildings 5-10 times less likely to be damaged during their lives than ones in California.

SEISMIC SAFETY TRADEOFFS

How much should community sacrifice in direct costs (private and public), reduced economic activity, and reduced public services over many years, to mitigate economic loss and fatalities in future earthquakes?

Seismic safety trades off with other desirable goals ("No free lunch")

Direct: funds strengthening schools not available to hire teachers, upgrading hospitals may require less patient care, etc..

Indirect: reduced economic activity (firms don't build or build elsewhere), job loss (or reduced growth), reduced tax revenue, etc..

Lives: proposed code might over time save a few lives per year; same sums invested otherwise (flu shots, defibrillators, highway upgrades, etc.) could save many more

No unique or correct answer - need to understand tradeoffs and help community who incur them decide (No such thing as OPM - “Other People’s Money” )
INITIAL COST/BENEFIT ESTIMATES: MEMPHIS

I: Present value: FEMA estimate of annual earthquake loss for Memphis area ($17 million/yr), only part of which would be eliminated by new code \( \sim 1\% \) of annual construction costs ($2 B).

II: Life-of-building: Use FEMA estimate to infer annual fractional loss in building value from earthquakes. If loss halved by new code, than over 50 yr code saves 1% of building value.

If seismic mitigation cost increase for new buildings with IBC 2000 >> 1%, probably wouldn't make sense.

Similar results likely from sophisticated study including variations in structures, increase in earthquake resistance with time as more structures meet code, interest rates, retrofits, disruption costs, etc.

More mitigation becomes cost-effective if technology lowers costs, or benefits increase via improved understanding of earthquake probabilities or (?) large earthquake probability increases with time.

SUMMARY

Major unresolved science issues:

What causes NMSZ & other intracontinental seismicity?

Does it concentrate on long-lived thermo-mechanically weak zones or migrate among many equivalent features?

If latter, recent seismicity alone overestimates hazards where earthquakes occurred, underestimates elsewhere

Needs:

Multidisciplinary investigation including GPS & heat flow

Recognize and explain that hazard estimates have large uncertainties

Careful study of building codes’ costs & benefits

Policy-making process to make tough choices for which there’s no unique or right answer