Estimating the complete stress tensor from microearthquake observations.

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During the 1970-1985 a number of 3-D rock stress observations were published. For a **fractured crust containing water the rock-mechanical conclusions make it possible to estimate the complete stress tensor from single fault plane solutions.**

Each observed microearthquake becomes a complete stress tensor observation.

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About fault plane solutions and the stress tensors

McKenzie 1969 **assumed** that **the fault plane** of a microEQ **is the only fracture** in the rock mass and showed that **then** FPS puts only weak constraints on the stress tensor.   But .....

there are **numerous fractures with many orientations** within the microEQ volume and it is not only needed that the fault plane have CFS = 0 but also: **all the other fractures must have CFS < 0.** These numerous restrictions are lost by the unrealistic one fracture assumption.

That is why **the FPS of a microEQ puts strong restrictions on the stress tensor.**

Some slides about *the value of using simple rock mechanics* follow.

Simple rock mechanics. The Mohr-Coulomb failure criterion applied to sliding on fractures filled with water.

So = fracture strength
T = shear stress
f = friction coefficient
Sn = normal stress
Sn-p = effective stress

The Mohr-Coulomb criterion is: T = So + f * Sn,
and with pore pressure p

T = So + f * (Sn-p)

which can be written in terms of principal stresses for *the least stable plane*:

(S1-S3)/2 = f * (S1+S3-2p)/2/sqrt(1+f*f) + So/sqrt(1+f*f)

where S1 = largest and S3 = smallest principal stress

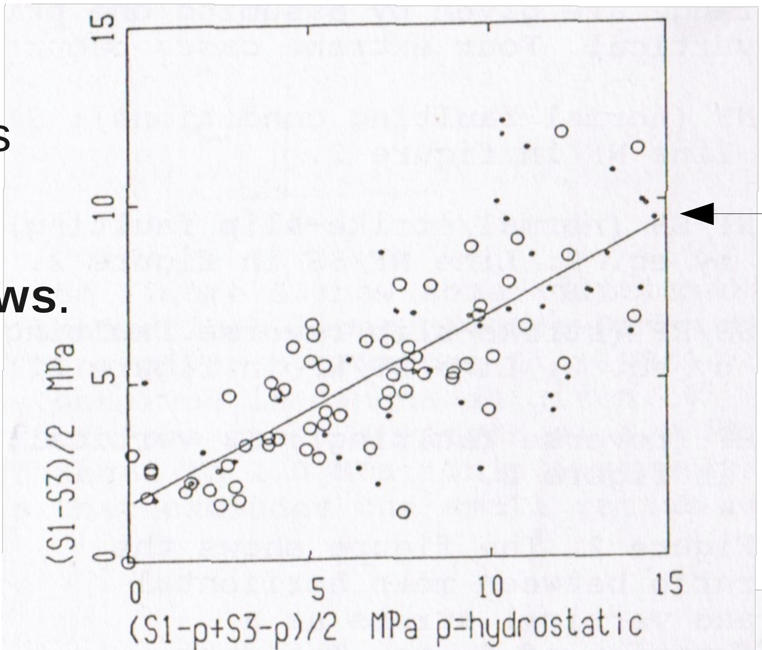
If 3-D stress observations plotted with (S1-S3) against (S1+S3-2p) defines a straight line as concluded by Jamison and Cook 1976 **one can estimate So and f from the line equation**.

Slunga 1987 got So = 1.9 MPa and f = 0.62 for granite crust.
See next slide.

B

Jamison and Cook 1976 concluded from rock stress measurements: **the shear stresses are as large as the frictional sliding allows**.

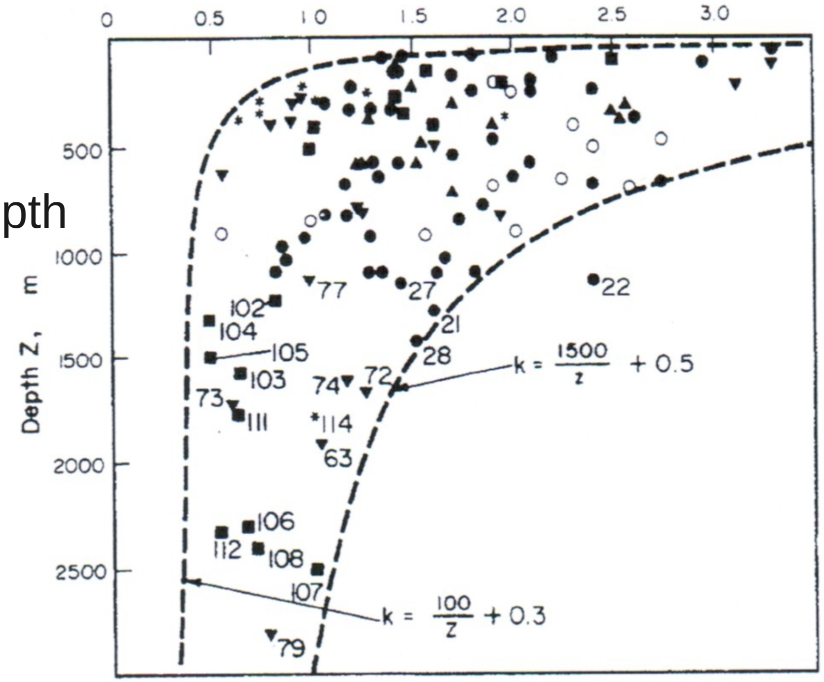
S1 largest principal stress
S3 smallest principa stress
p water pressure



C

Slunga 1987 checked the conclusion with *a new set of stress measurements*. The line gives So and f and with use of these values we get the lines below. The dots should be between the leftmost and rightmost lines plus below the p-lines.

k= (SH+Sh)/2/Sv $k = \frac{\sigma_{h\,av}}{\sigma_v}$



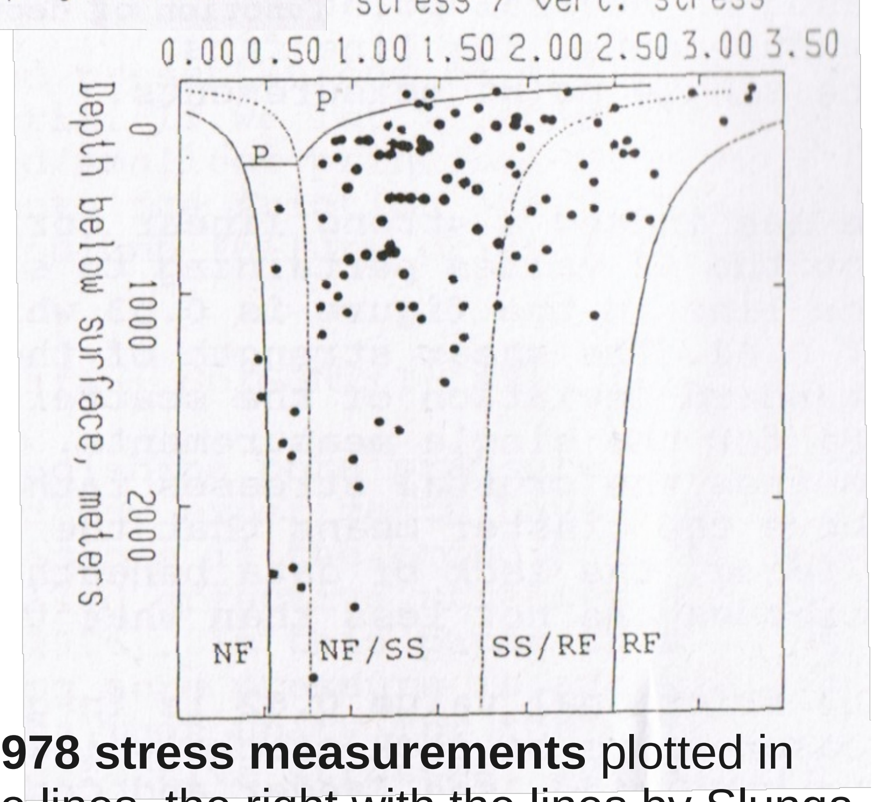
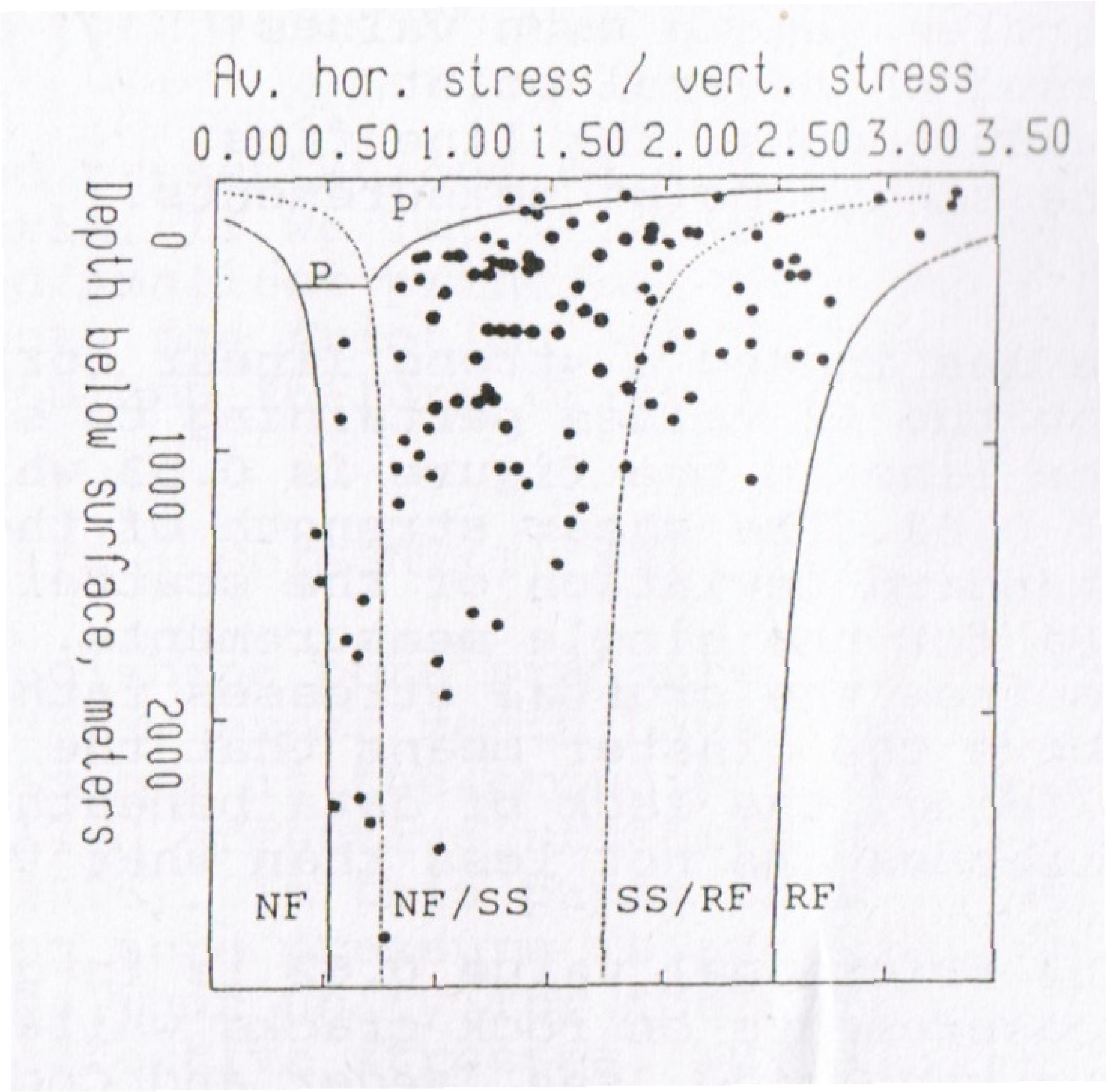


Fig. 2.

These two figures show the **Brown and Hook 1978 stress measurements** plotted in a k versus depth diagram. The left with nonsense lines, the right with the lines by Slunga 1987.

D

Possible k-values at different depths for a fractured crust with hydrostatic water pressure p, So=1.9MPa, f=0.62.



The top lines marked p indicate that no points should be above as S3 cannot be less than p.

NF = normal faulting
RF = reverse faulting
NF/SS and RF/SS show the limits where strike-slip is dominating

The lack of large k-values at depths exceeding 750 meters is striking.

If the water pressure p sometimes is larger than hydrostatic it would lead to a lack of larger k-values.

The k-values from the Brown and Hoek data set, the lines from the Slunga data set.

The **QuakeLook stress method** assumes

- **the crust is very fractured with water in the fractures**

- the **rock has a limited strength**

- the **stress tensor fields are heterogeneous** at all scales (deformations by block movements)

- the **vertical stress balances the overburdon** (lithostatic vertical stress)

- the **Jamison and Cook conclusion holds** (the straight line)

- the **water pressure p is lowest possible** for keeping **some fractures open**

All these assumptions are quite reasonable,

any questions or comments?

The effect of *limited rock strength* gives a layered crust

Close to the surface waterfilled fractures are connected up to the surface which means that the water pressure will be hydrostatic.

At deeper depths the water pressure increases hydrostatically while the rock pressure increases with the vertical pressure. The effecticve normal stress increases with the depth z:

Sneff(z) = Sn(z) – p(z) = Sn(z1)-p(z1) +(rho(rock) – rho(water))*(z-z1)*g

Where z1 is a depth where we assume we know p(z1).

Sneff(z) will increase with the depth below z1 until the limited strength of the rock means that all fractures will close, no fluid flow possible.

If we assume that any fracture will be closed for Sneff=13 MPa we get that the maximum value of z-z1 is (if Sn(z1)=p(z1)):

maximum (z-z1) = 13e+6/(rho(rock)-rho(water))/g = **800 m (about)**.

Thus, the vertical sizes of water flow connected crustal volumes will be less than some 800 m if the rock fractures close at 13 MPa.

The smallest possible pore pressure within the waterfilled crust

The lowest possible water pressure within the crust equals the smallest possible Sn (normal stress) for all possible fracture orientations and stress types. This Sn equals S3 for a normal faulting stress type having S1 vertical. **The linear relation S1-S3 -- S1+S3-2p** gives

pmin(z1) = Sv(z1) - 2. * So /((sqrt(1+f*f)-f)

Thus the smallest possible water pressure below z1 will be

pmin(z) = Sv(z1) – 2.*So/((sqrt(1+f*f)-f) + (z-z1)*rho(water)*g

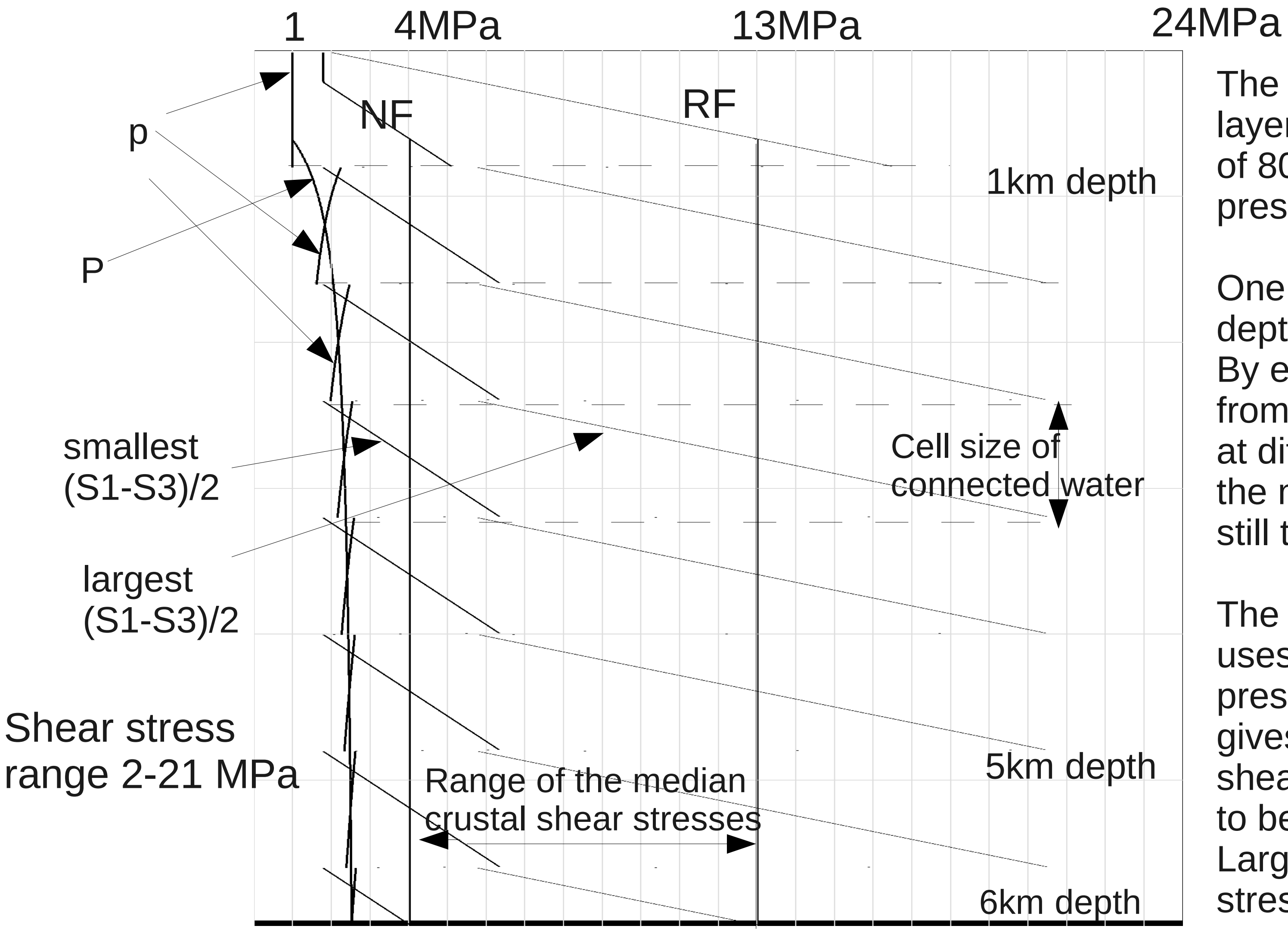
where Sv(z1)= rho(rock)*z1*g

With a rock strength giving the closing effective stress to be 13 MPa this expression will be valid for 0<z-z1<800m ...... the crust will have a layered structure.

With the closing stress of 13 MPa, So=1.0MPa, and f=0.62 we get the following water pressure and shear stresses ranges.

Shear stresses, (S1-S3)/2, within a wet “Icelandic” crust 0-6 km depth

The resulting water pressure, pw, and range of possible shear stresses within
an “Icelandic” crust, p=pw/phydrostatic and shear stress (S1-S3)/2 MPa



1 4MPa 13MPa 24MPa

NF

RF

p

P

smallest
(S1-S3)/2

largest
(S1-S3)/2

Shear stress
range 2-21 MPa

1km depth

Cell size of
connected water

5km depth

Range of the median
crustal shear stresses

6km depth

The resulting crust will be layered with thicknesses of 800m if the closing pressure is taken as 13 MPa.

One cannot know the exact depth limits of the layers. By estimating the stresses from several earthquakes at different depths and use the median values one expect still to get good estimates.

The QuakeLook method uses the smooth water pressure curve, P, which gives the range of possible shear stresses estimates to be 4-13 MPa.
Larger strike-slip EQs should stress drops less than 10 MPa.

Weaker or hotter crust gives smaller “cell sizes” resulting in smaller shear stress.

The QuakeLook stress tensor estimate for single microearthquakes Slunga 2006.

The fault plane solution of a microearthquake, with the Coulomb failure criterion (applied to fractured rock), puts 3 constraints on the rock stress tensor (the directions of S1, S2, and S3).

The requirement that CFS=0 on the fault plane gives 1 constraint.

The vertical stress can be taken equal to the lithostatic stress which means 1 constraint on the stress tensor.

Thus the rock mechanical approach puts 5 constraints on the stress tensor - one more is needed.

The QuakeLook method, Slunga (2006), gets the missing constraint by assuming that the deviatoric elastic energy is as small as possible.

Thus ---- **for each microearthquake the complete stress tensor causing the EQ slip can be determined**.

Each microEQ will be a point estimate of the stress tensor field.

Stress maps: **median values** within small squares containing **at least 20 events**.
Circles scale with (S1-S3)/2=shear stress, lines scale with SH-SV and Sh-SV.

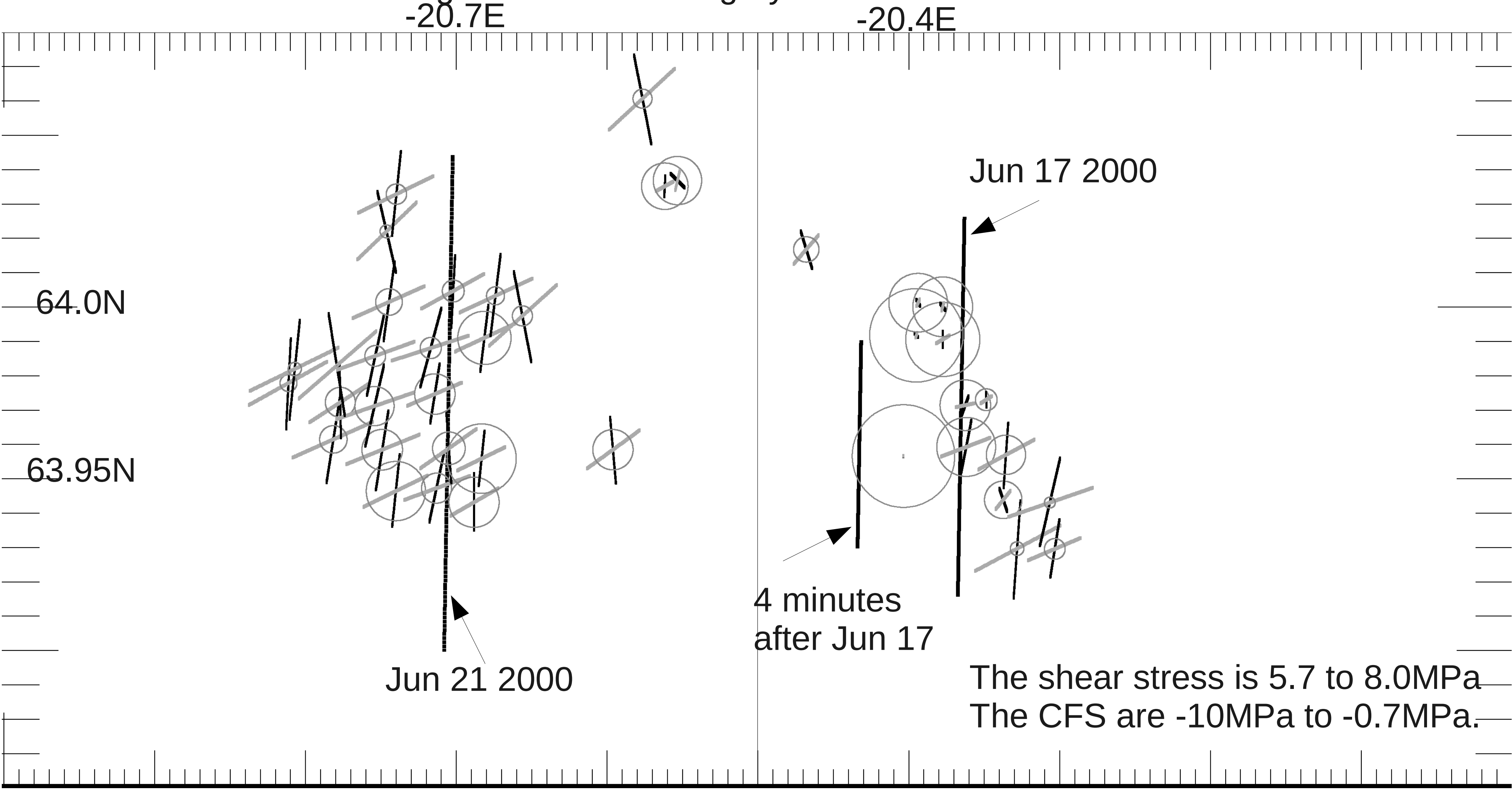
The size of each square is 660x660 meters.

Note that each stress estimate is independent (each event used only once).

The shear stresses scales between 5.5MPa and 7.8MPa. The Shor-SV scales within -10.7MPa and 2.4MPa.

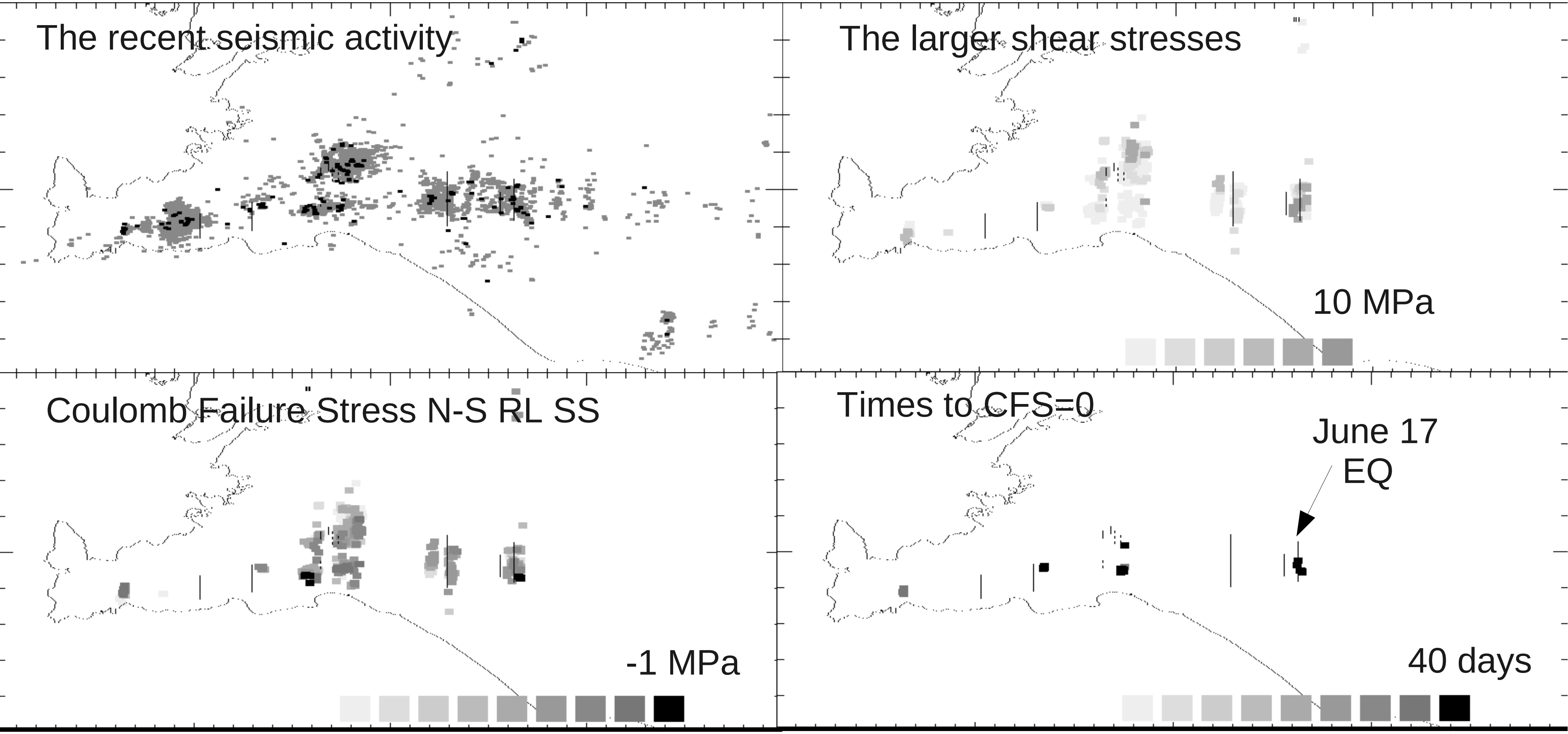
The map size is 25x25 sqkm. The stresses are based on 80,600 events 1996-2000.

Stress maps before the two M=6.6 June 2000 EQs. The circles scale with shear stress (S1-S3)/2, and the lines show least stable vertical fault directions. Black lines indicate right-lateral SS and gray lines show left-lateral



The shear stress is 5.7 to 8.0MPa
The CFS are -10MPa to -0.7MPa.

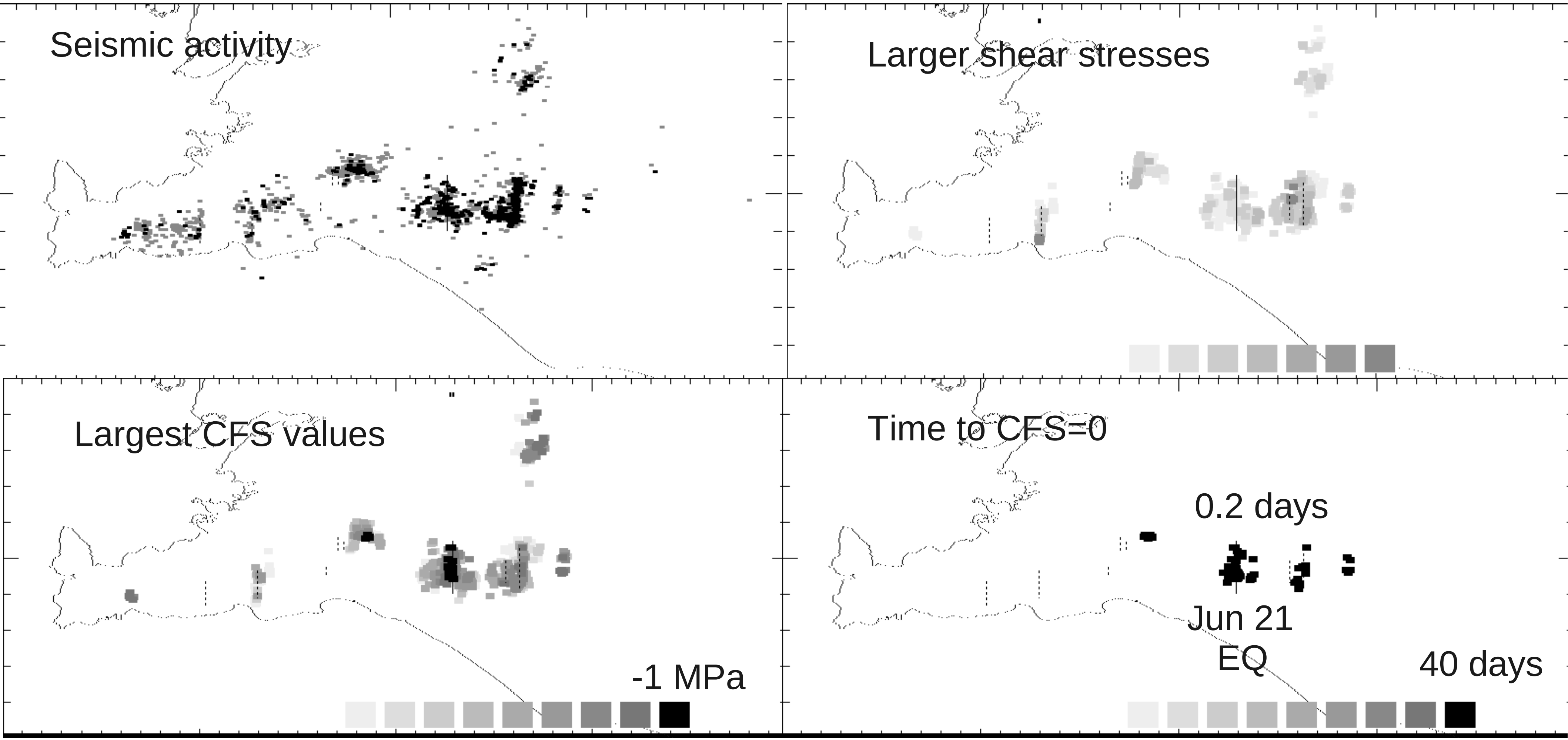
The estimates are median values within squares (0.015 degrees) based on the microearthquakes observed between Jan 1 1996 and Jun 17 2000.



These figures show the situation a few hours before the June 17 2000 M=6.6 EQ
all solid N-S lines were EQs that occurred within seconds, minutes, or 3 days.

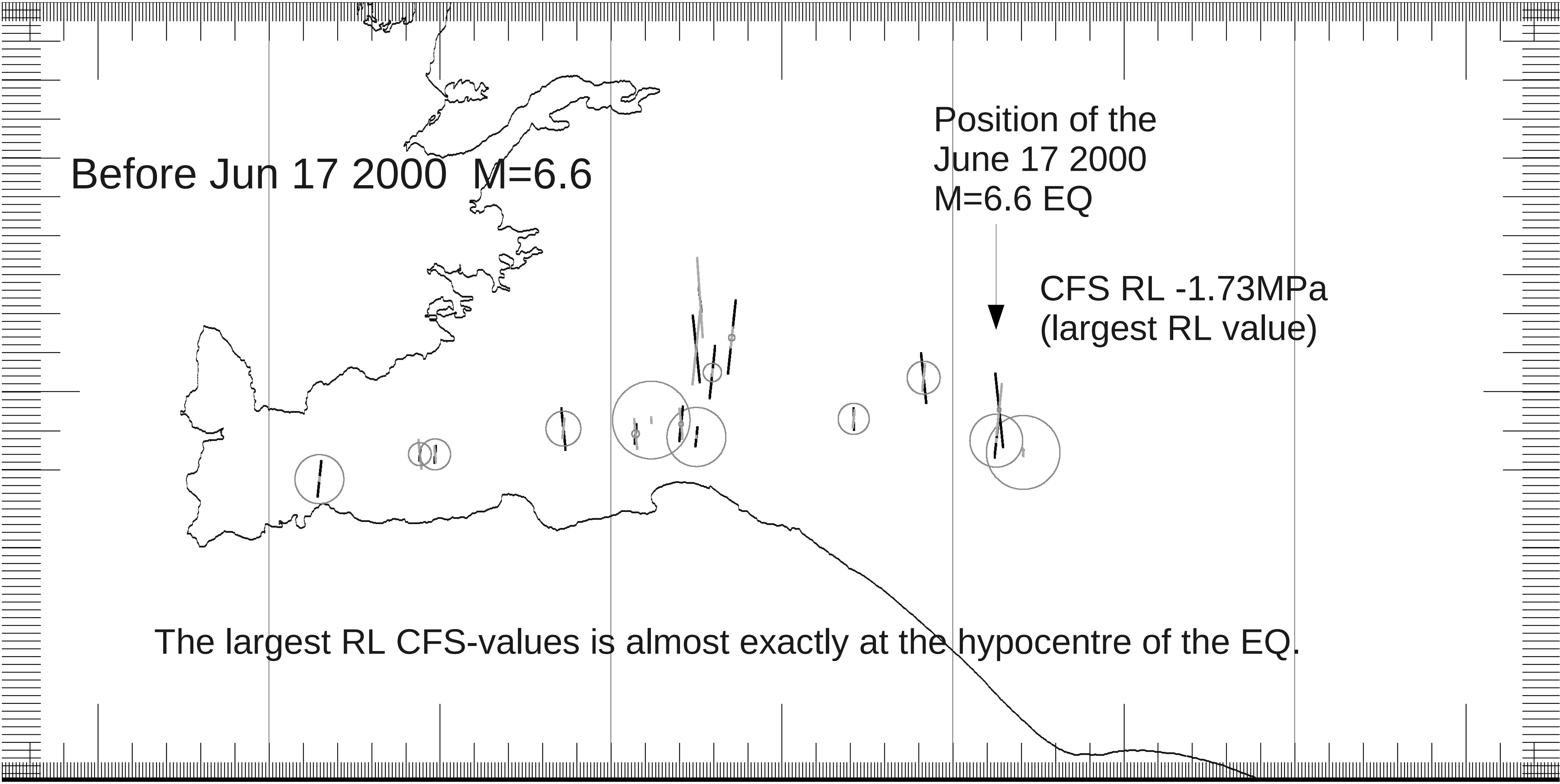
The output maps from the QuakeLook EQ warning implemented at IMO in Reykjavik. Medians of 6 close events within 21 days compared to 1 year earlier.

The EQ warning applied to Jun 17 2100 – Jun 21 0030 before the M=6.6 EQ Jun 21 2000



Again medians of 6 close events during 24 hours compared to the activity after Jun 17

Stress snap shot, median of 2 last events June 7 1540 – June 17 1540 2000.
Circles scale with S1-S3, lines scale with CFS, black RL, gray LL.
The CFS values are computed for vertical N-S +/- 6degrees strike slip faults.



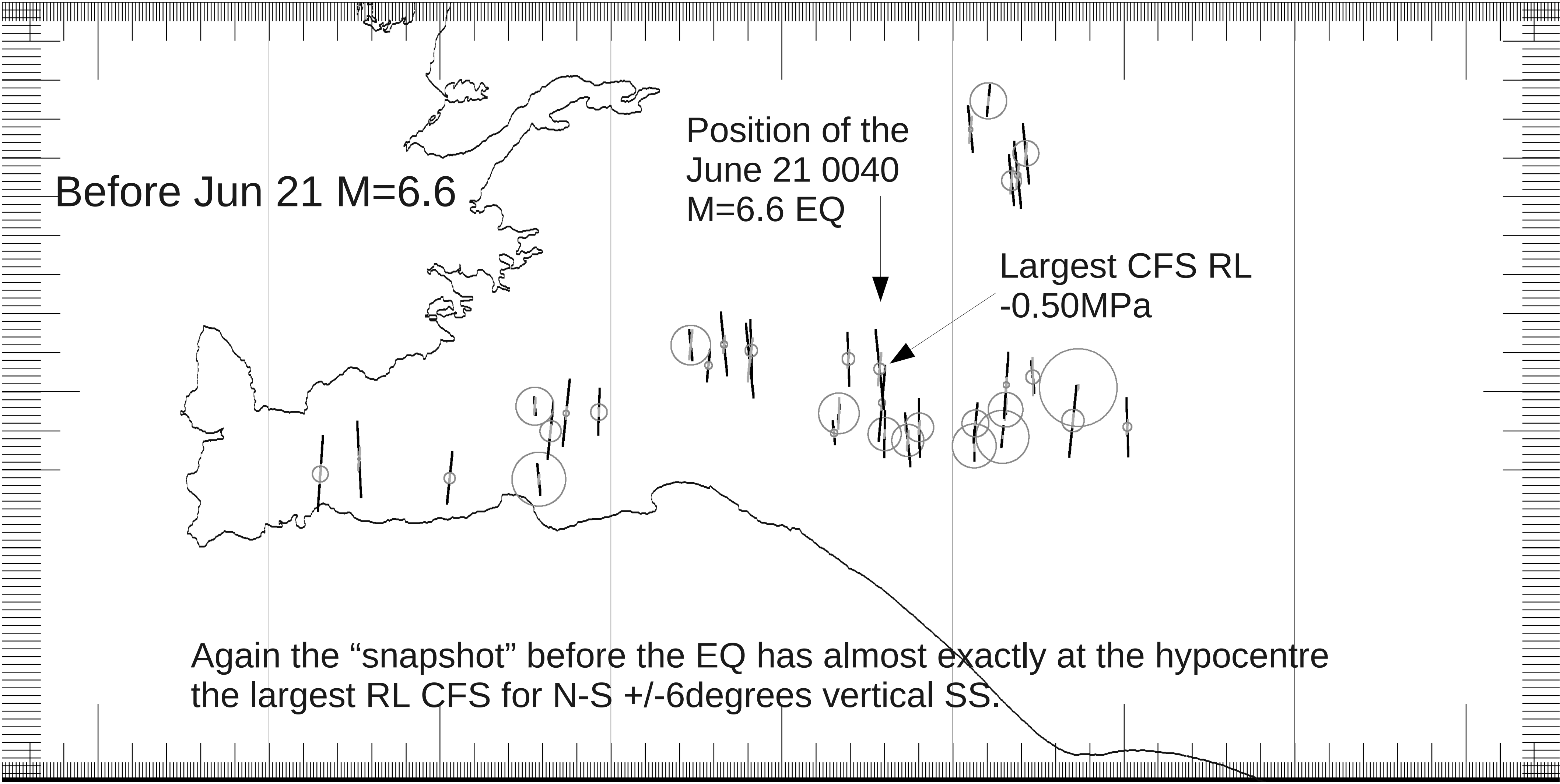
Before Jun 17 2000 M=6.6

Position of the
June 17 2000
M=6.6 EQ

CFS RL -1.73MPa
(largest RL value)

The largest RL CFS-values is almost exactly at the hypocentre of the EQ.

Stress snap shot, medians of last three events June 20 0000 – June 21 0000 2000.
Circles scale with S1-S3, lines CFS NS SS, black RL, gray LL.



Again the “snapshot” before the EQ has almost exactly at the hypocentre the largest RL CFS for N-S +/-6degrees vertical SS.

Comments

The method requires microEQs, thus only stresses with CFS=0 can be observed.

The underlying idea is that the CFS on the numerous fractures have CFS close to zero for some slip direction (Jamison and Cook 1976) and that the in situ stresses are quite heterogenous. Thus, any stress change (or pore pressure increase) will cause microEQs. The stresses given by the present method are then indicating the type of stress change.

If the stress changes are similar to the general tectonic loading of the area one then expects a larger number of triggered microEQs (foreshocks) as that stress type should be most common. One will observe increased CFS for the major source mechanism.

This may explain why the QuakeLook EQ warning algorithm seems to point out the places of the coming EQs.

Thank you for listening!

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