



INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION



INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

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**WORKSHOP
GLOBAL GEOPHYSICAL INFORMATICS WITH APPLICATIONS TO
RESEARCH IN EARTHQUAKE PREDICTIONS AND REDUCTION OF
SEISMIC RISK**

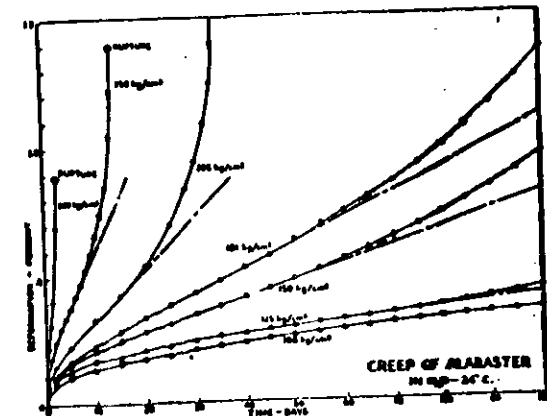
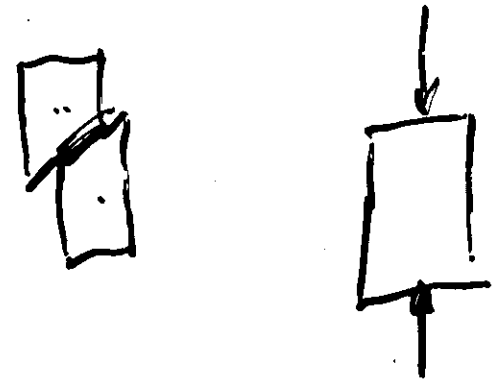
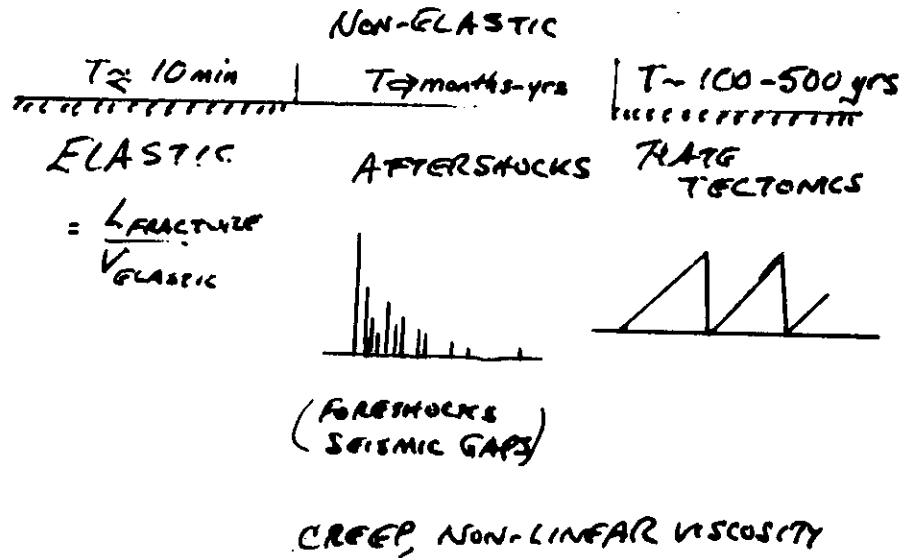
(15 November - 16 December 1982)

**LABORATORY CONSTRAINTS ON PHYSICAL MODELS
THE PHYSICS OF FRACTURE**

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**University of California
Los Angeles
U.S.A.**

TIME SCALES



Chemical Kinetics
Activation Process
Stress Corrosion
(rate of H_2O)

$$t_f = t_0 e^{-E/kT} \quad E = 0.6 \text{ eV}$$

a large number of
references:

- Glass: Preston et al, Nature 156, 1946
J. App. Phys. 17, 1946
- Metals: Zhurkov, Int. Fract. Mech., 1, 1965
- Rubbers: Griggs, Bull. G. S. A., 51, 1950
- Plastics: Leon Sobolev, Zhurkov, loc. cit.
- Metals: Cherepanov, Alekhin & Brittle Fract. (McGraw-Hill 1977)

508

⑥

40

TABLE 1.—Properties of alabaster in wet creep tests at different stresses
(Gypsum in each experiment subject to constant load, in the presence of its own saturated aqueous solution, at 20°C., $\sigma_1 = \sigma_2 = 0$)

Compressive stress ($\sigma_1 = \sigma_2$ in kg/cm ²) σ	Steady-state velocity (millionths per day) v_s	Deformation before fracture (per cent) ϵ	Duration of test (to fracture) (days) t_f	Equivalent viscosity (poises) $\times 10^6$ η
300	2000	5.3	2.45	42
280	440	1.29	13.88	1.60
208	218*	2.1*	48*	2.04
181	100	3.0	132	5.11
166	77.0	3.3	288	0.04
150	66.5	>1.05	>110	0.36
125	24.5	3.3	208	14.4
108	1.0*	>2.1*	>100*	41.6 (??)
	2.6	>4.1	7/200	22.2

* Average of three duplicate tests.

Properties of same gypsum when dry:
Strength (short-time) = 520 kg/cm²
Deformation before fracture = 38% (primarily elastic)
Equivalent viscosity = $> 6 \times 10^6$ at 420 kg/cm²

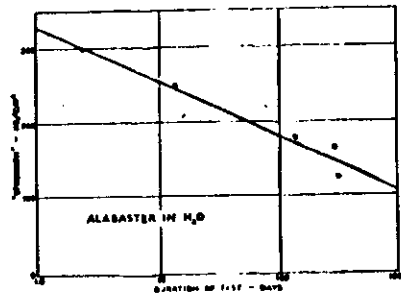
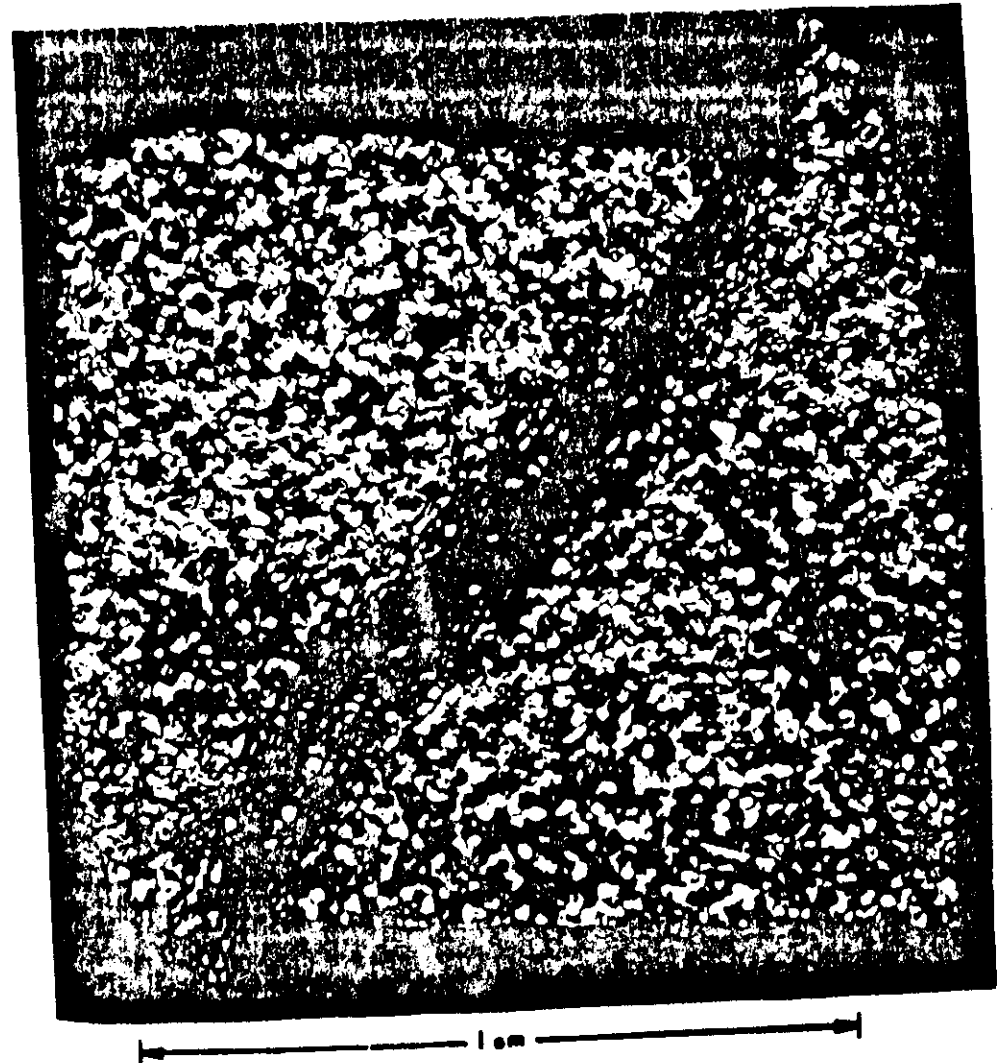
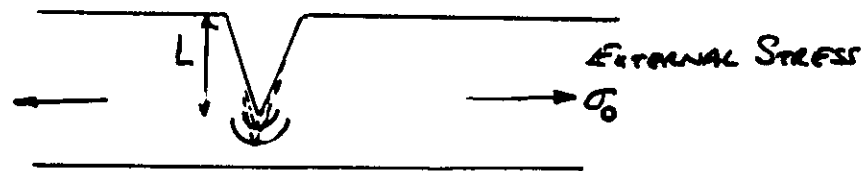


FIGURE 10.—Strength of alabaster as a function of duration of test
Data from experiments of Figure 9.



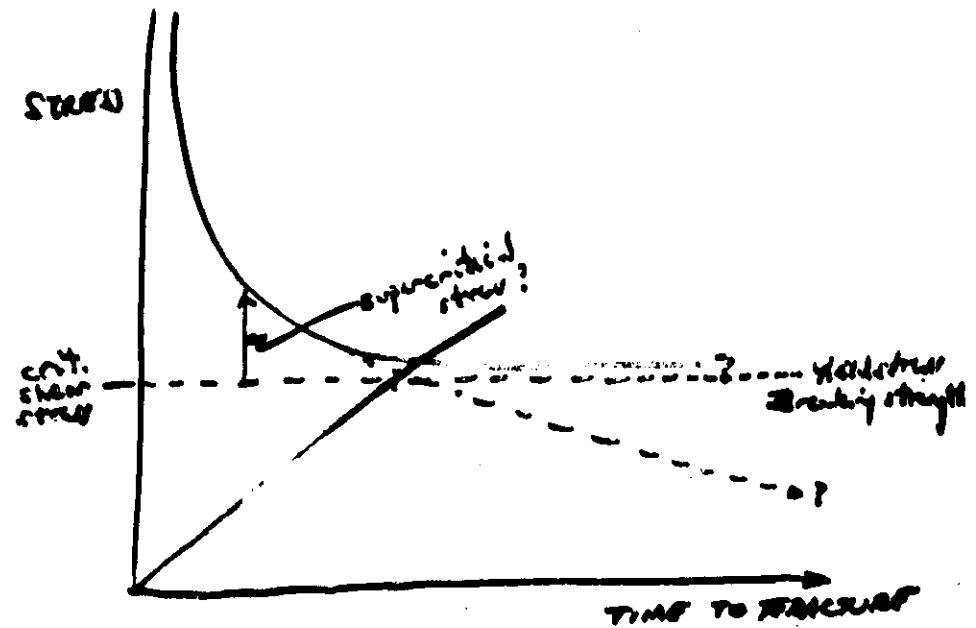
ST. PETER SAND 40-66 MESH
Compacted at 500°C., 5 kb confining pressure, 1 kb interstitial water pressure, then compressed 40 per cent.
Temperature and fluid pressures kept constant. Thick copper jacket did not rupture despite shear offset at ends.



- $V = \frac{dL}{dt} \sim e^{\frac{\sigma_0 \sqrt{L}}{kT}} \times \text{const}$

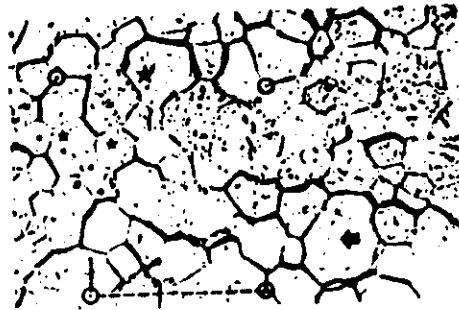
activation process!

- Process much accelerated
in presence of water
IN ROCKS
SOLUTION & ROCKY STALLIZATION





a



b



c



d



e



f

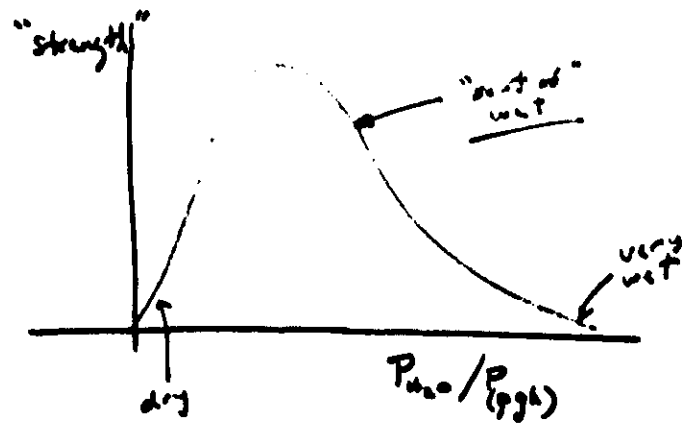
100 μm

The Role of Water.

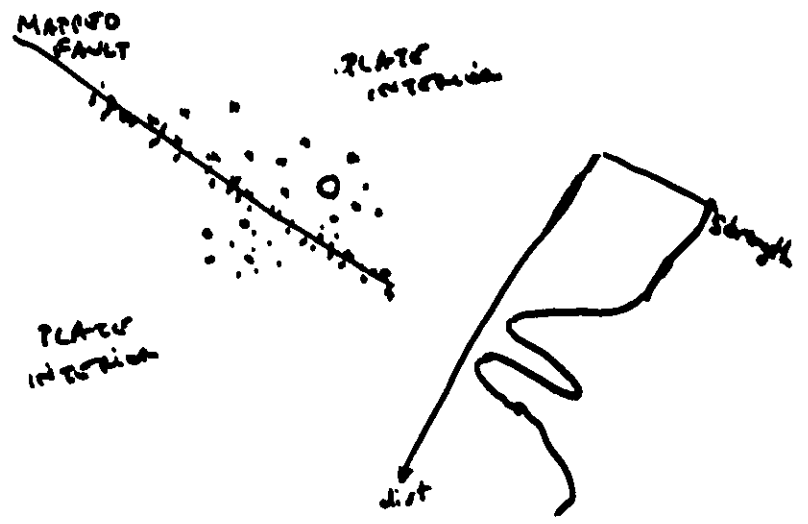
1. Why does wet sand have cohesive strength?
surface tension



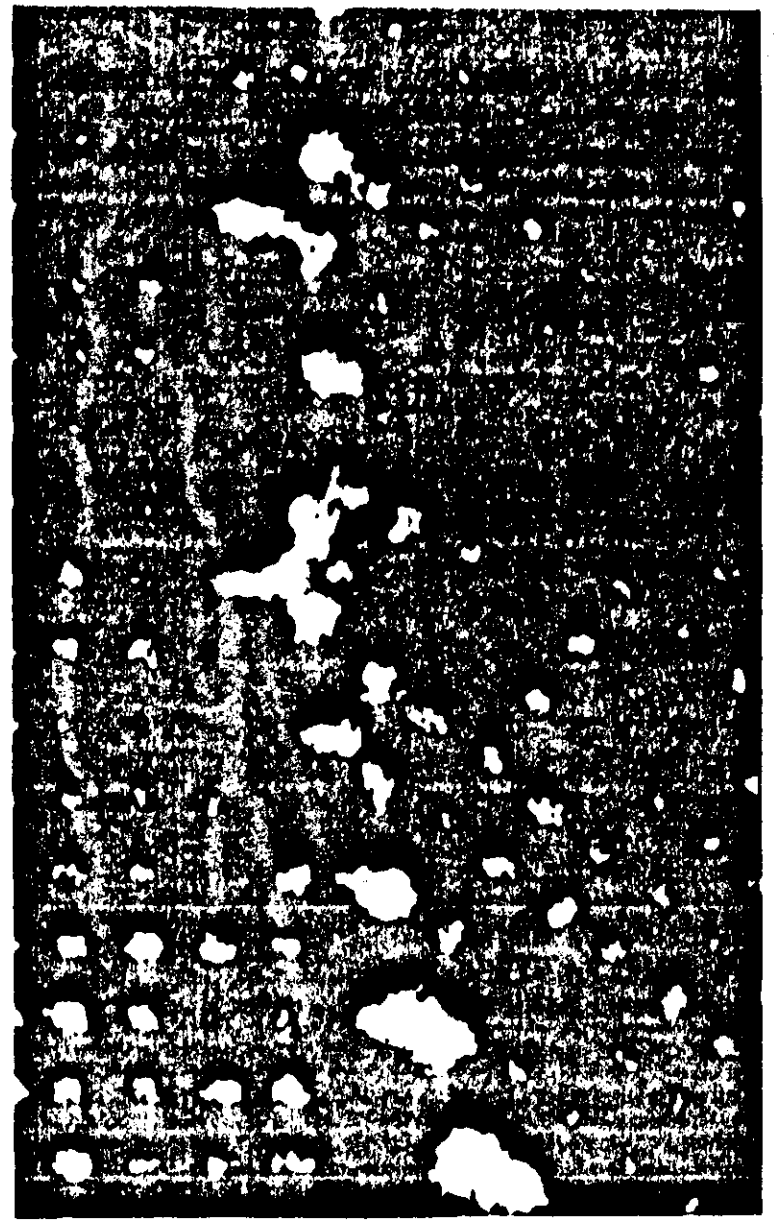
Figure 4. Cracking and twinning in sodium nitrate in dextral shear zone. Intergranular crack propagation and twin inception near small stars in b and d; twin widening at stubby arrow; microfracture dilation at d and elsewhere. Sample thickness is about 30 μm.



1. experiments on gouge
2. Diffusion mylonite



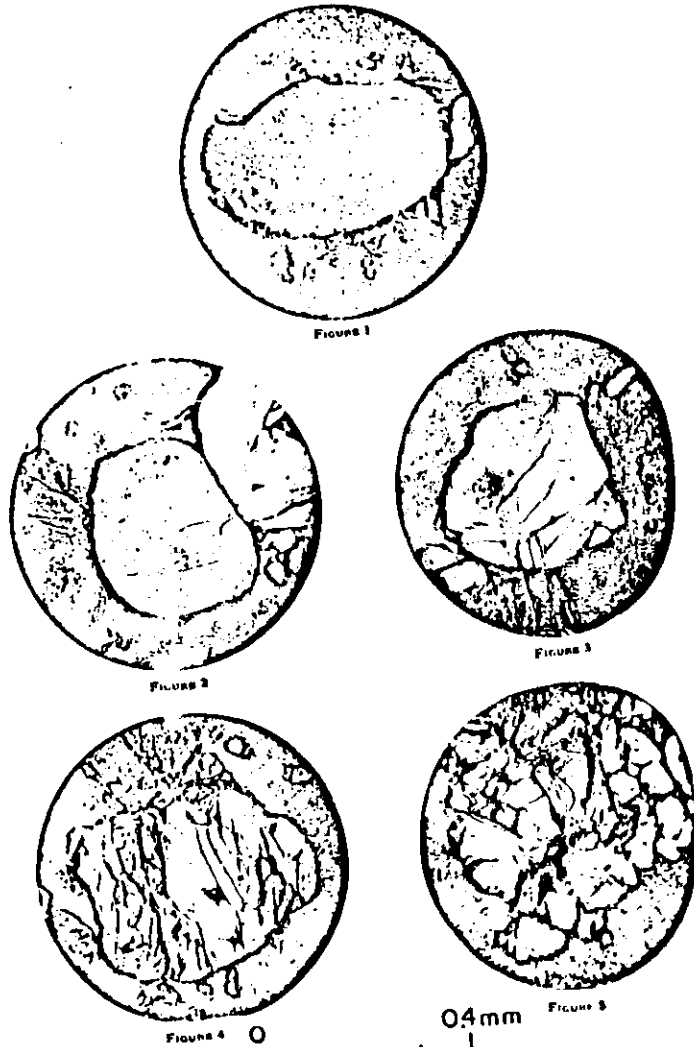
Faceted MIO boundary: The white areas represent the areas between atom columns and show the relatively wide spaces at the grain boundary. The segment of the 38° boundary on the left is asymmetric with the grain boundary parallel to a (100) plane in the lower half of the bicrystal. The segment on the right is approximately symmetric.



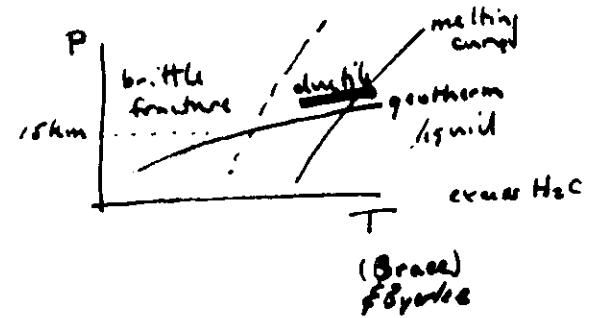
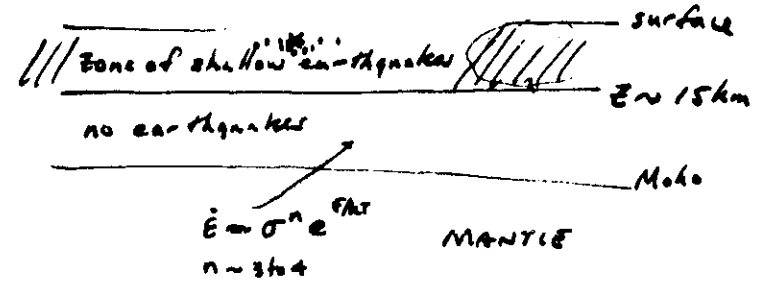
K. L. Merkle, Argonne National Laboratory

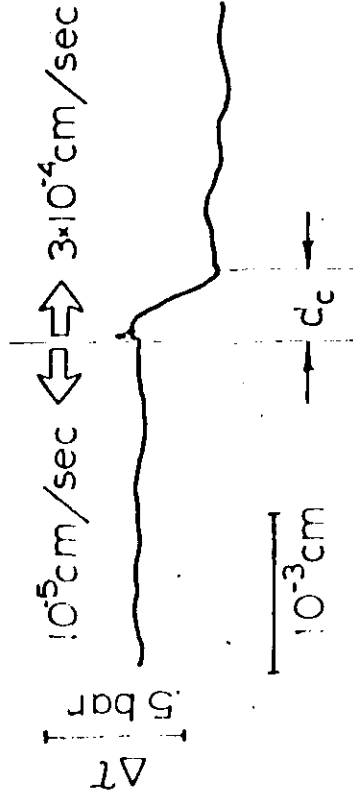
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Is the viscosity of the earth everywhere of the same nature?



ST. PETER SAND SHOWING VARIOUS INTENSITIES OF FRACTURING

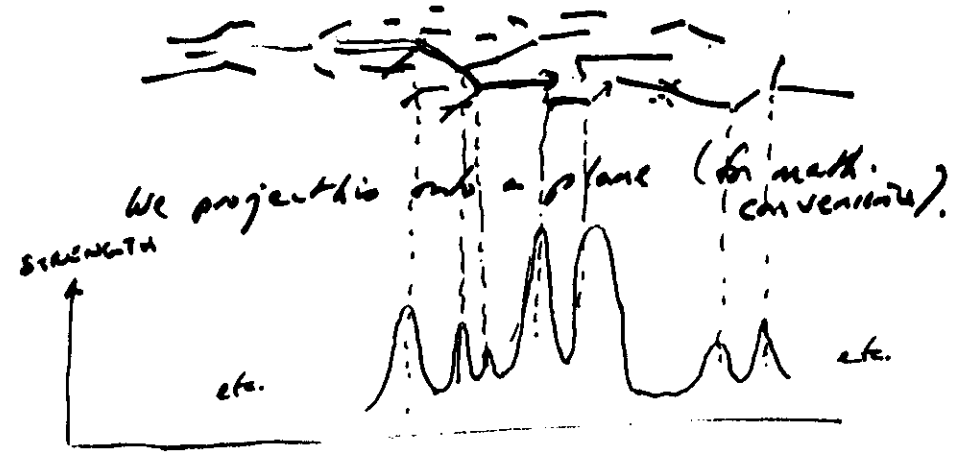




effect of static friction
 $m \approx m_0 \ln(1 + at)$
 Dietrich
 JGR 1979

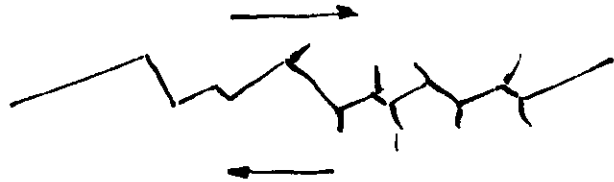
Figure 5

What is the yield strength of a barrier
 to a wall, if the strength depends on
 geometry?

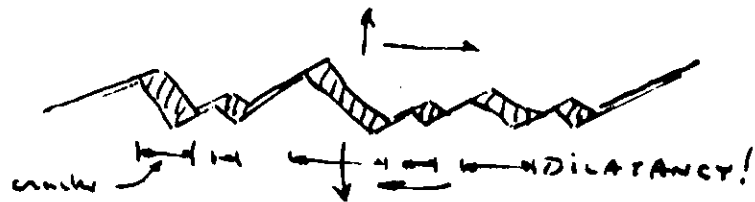


dynamic friction

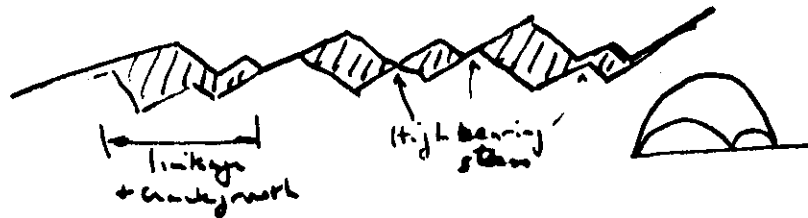
Consider an irregular crack surface which we model as a sawtooth. We subject the elastic medium to a shear stress.



In order that lateral motion takes place, one crack surface must "ride" upward over the other. Thus transverse motion must take place.

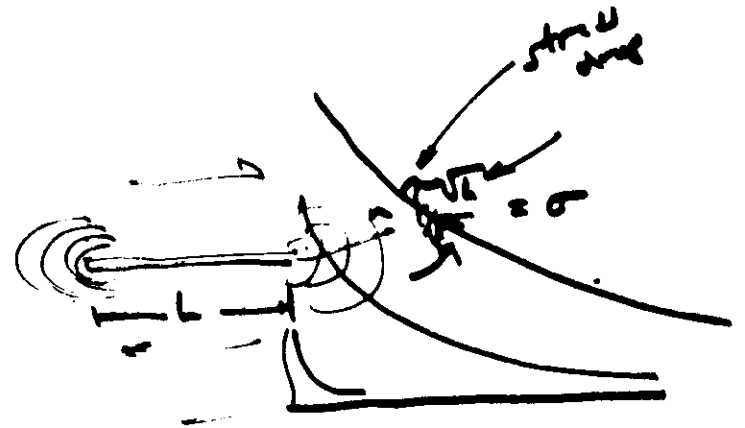


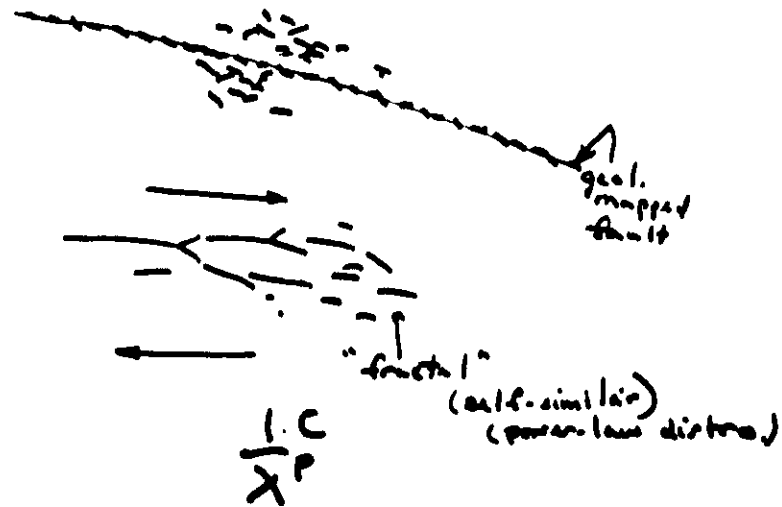
When sliding becomes too large, cracks begin to link up.



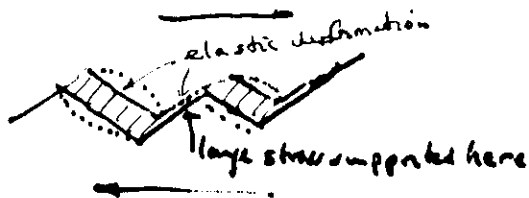
What keeps a crack "open"?

Healing!

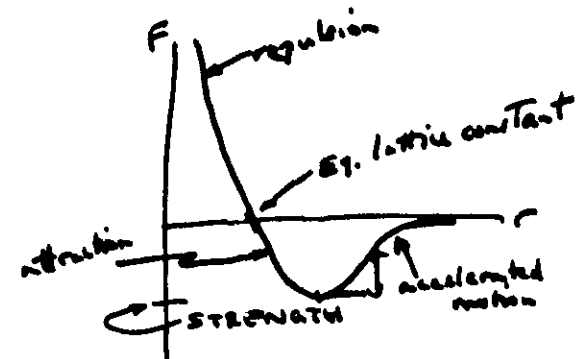
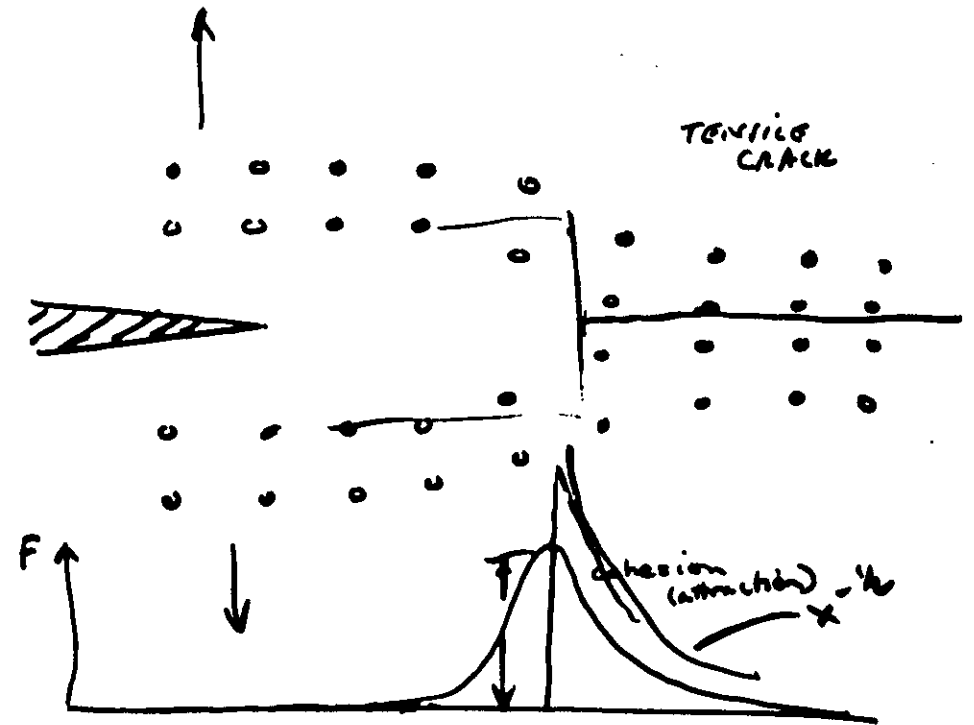




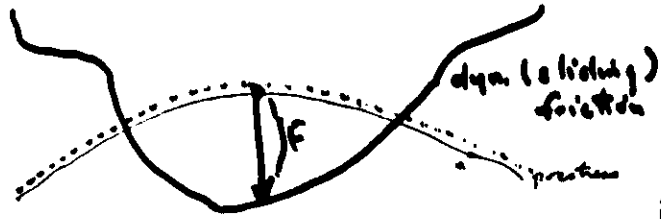
linkage of cracks
(keep cracks open for awhile?)



(role of water in recrystallization) what are angles of the saw-teeth?
how high are the saw-teeth?
(wave len. λ)



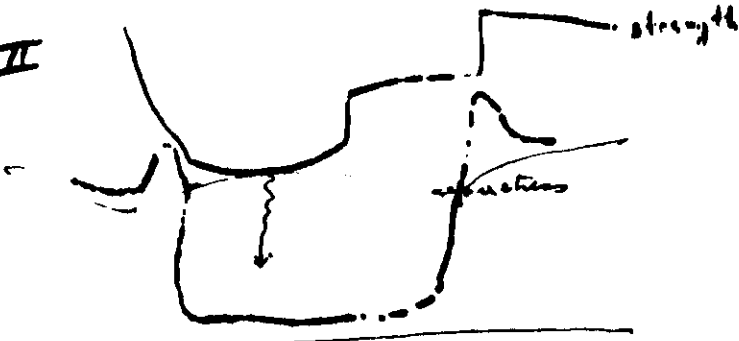
I



$$F = ma$$

Burridge
& Halliday
Geophys.
R.A.S.
1972±1

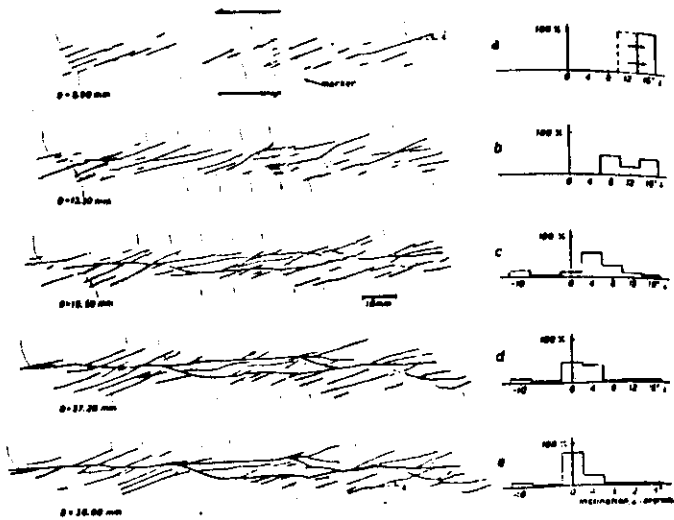
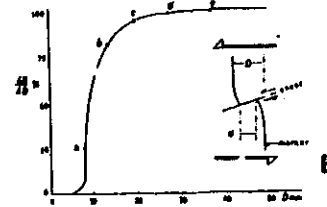
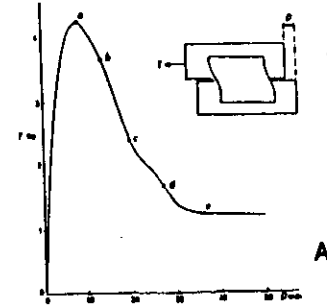
II



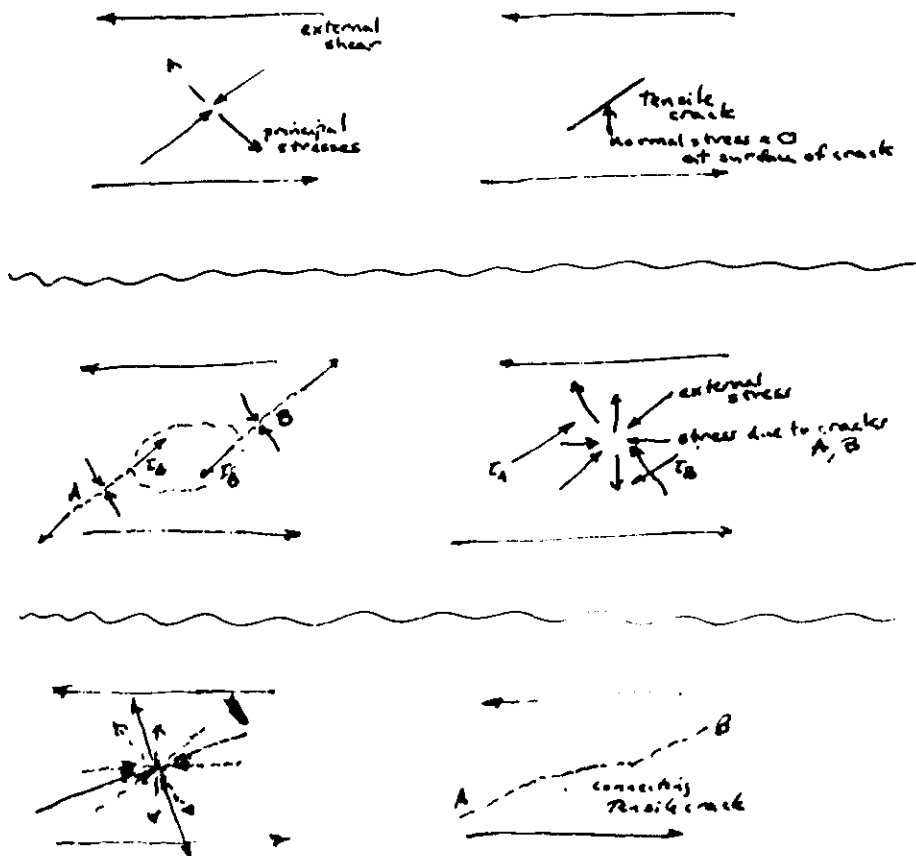
"the unbreakable substance"



moderation of the
in finity is
the redistribution
stress.

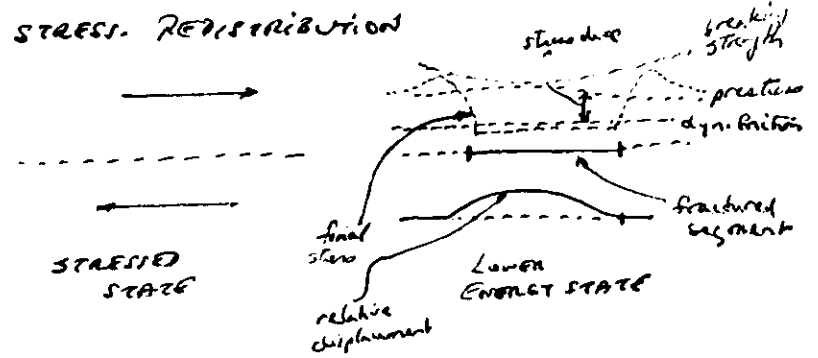


Tchalenko

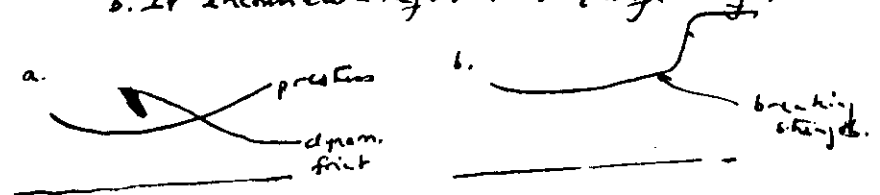


PHYSICS OF FRACTURE (simplified version)

1. A FRACTURE IN A PRESTRESSED SOLID LEADS TO A STRESS REDISTRIBUTION



2. A fracture slips because
 - a. It enters a region where the strength becomes negative
 - b. It encounters a region of very large strength



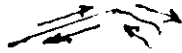
I personally believe that model (b) is the mechanism (the barrier or energy model).

3. CREEP IS AN IMPORTANT ACCOMPANIMENT TO THE EARTHQUAKE EVENT

This process must involve some sort of (non-linear) rheology. The TIME INTERVAL BETWEEN AFTERSHOCKS IS TOO SHORT TO BE ACCOUNTED FOR BY PLATE TECTONICS. PRE AND POST-SHOCK CREEP IS OBSERVED IN THE FIELD.

An attack on the basic assumption
(that we know how to project geometry onto
a planar stress distribution)
requires that:

- 1. We study the three-dimensional nature of faulting.



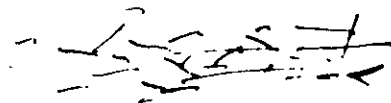
- a. Importance of higher-order multipolar sources.
- b. HEALING

Other horrible problems:

- 2. Coupling of dynamical rupture with quasi-static rupture
- 3. Coupling of fluid diffusion with fracture (stress diffusion)
... and vice-versa.
 - a. Fluid flow in conduits of irregular shape
 - b. Fluid flow (and stress diffusion) in tortuous geometries



TORTUOSITY



Some Additional Problems & Reminders

1. Statistics: Not only useful to delineate major trends, but also extremely important to give estimates of accuracy of determinations
examples: Seismic Risk Maps, of recurrence times
Extreme value statistics
2. Dilatancy: Where does the extra volume go?
(where does the matter go?)
Role of the surface of the earth.
3. Elasticity: During the process of opening up (diagonal) cracks, the "grains" deform elastically
4. What is the nature of friction?
The function of GOUGE (mylonite)
5. Based on what we know at this point, can we construct a model in which
 - a. Small egs. occur off (away from) (geologically mapped) faults
 - b. Large egs. only occur on mapped faults
 - c. Aftershocks occur
6. What is influence of healing?
what is nature of healing?
7. What is role of water?

ANY THEORETICAL MODEL
If Earthquakes are MUST SATISFY.

perfectly periodic

• or (Poisson) random

we do not have to bother to construct complex models for their occurrence.

Terminale

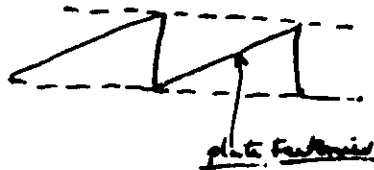


plate fasteners

If earthquakes are **CLUSTERED**

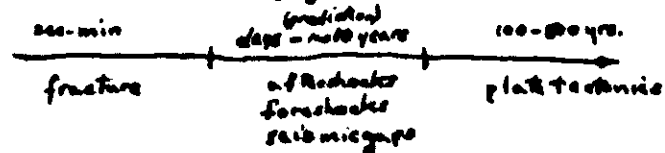
INTERACTION: we must develop an interactive model.

⇒ Stress redistribution due to fracture

But stresses are redistributed elastically
TOO FAST!

We cannot account for aftershocks

3 time scales of changing stress



We need a time delay: RHYTHM

⇒ Creep (non-elastic) process involves time delays

→ plus geometrical constraints
FAULTING!

Large earthquakes (especially) must take into account finite size of fractures

11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. 43. 44. 45. 46. 47. 48. 49. 50. 51. 52. 53. 54. 55. 56. 57. 58. 59. 60. 61. 62. 63. 64. 65. 66. 67. 68. 69. 70. 71. 72. 73. 74. 75. 76. 77. 78. 79. 80. 81. 82. 83. 84. 85. 86. 87. 88. 89. 90. 91. 92. 93. 94. 95. 96. 97. 98. 99. 100. 101. 102. 103. 104. 105. 106. 107. 108. 109. 110. 111. 112. 113. 114. 115. 116. 117. 118. 119. 120. 121. 122. 123. 124. 125. 126. 127. 128. 129. 130. 131. 132. 133. 134. 135. 136. 137. 138. 139. 140. 141. 142. 143. 144. 145. 146. 147. 148. 149. 150. 151. 152. 153. 154. 155. 156. 157. 158. 159. 160. 161. 162. 163. 164. 165. 166. 167. 168. 169. 170. 171. 172. 173. 174. 175. 176. 177. 178. 179. 180. 181. 182. 183. 184. 185. 186. 187. 188. 189. 190. 191. 192. 193. 194. 195. 196. 197. 198. 199. 200. 201. 202. 203. 204. 205. 206. 207. 208. 209. 210. 211. 212. 213. 214. 215. 216. 217. 218. 219. 220. 221. 222. 223. 224. 225. 226. 227. 228. 229. 230. 231. 232. 233. 234. 235. 236. 237. 238. 239. 240. 241. 242. 243. 244. 245. 246. 247. 248. 249. 250. 251. 252. 253. 254. 255. 256. 257. 258. 259. 260. 261. 262. 263. 264. 265. 266. 267. 268. 269. 270. 271. 272. 273. 274. 275. 276. 277. 278. 279. 280. 281. 282. 283. 284. 285. 286. 287. 288. 289. 290. 291. 292. 293. 294. 295. 296. 297. 298. 299. 300. 301. 302. 303. 304. 305. 306. 307. 308. 309. 310. 311. 312. 313. 314. 315. 316. 317. 318. 319. 320. 321. 322. 323. 324. 325. 326. 327. 328. 329. 330. 331. 332. 333. 334. 335. 336. 337. 338. 339. 340. 341. 342. 343. 344. 345. 346. 347. 348. 349. 350. 351. 352. 353. 354. 355. 356. 357. 358. 359. 360. 361. 362. 363. 364. 365. 366. 367. 368. 369. 370. 371. 372. 373. 374. 375. 376. 377. 378. 379. 380. 381. 382. 383. 384. 385. 386. 387. 388. 389. 390. 391. 392. 393. 394. 395. 396. 397. 398. 399. 400. 401. 402. 403. 404. 405. 406. 407. 408. 409. 410. 411. 412. 413. 414. 415. 416. 417. 418. 419. 420. 421. 422. 423. 424. 425. 426. 427. 428. 429. 430. 431. 432. 433. 434. 435. 436. 437. 438. 439. 440. 441. 442. 443. 444. 445. 446. 447. 448. 449. 450. 451. 452. 453. 454. 455. 456. 457. 458. 459. 460. 461. 462. 463. 464. 465. 466. 467. 468. 469. 470. 471. 472. 473. 474. 475. 476. 477. 478. 479. 480. 481. 482. 483. 484. 485. 486. 487. 488. 489. 490. 491. 492. 493. 494. 495. 496. 497. 498. 499. 500. 501. 502. 503. 504. 505. 506. 507. 508. 509. 510. 511. 512. 513. 514. 515. 516. 517. 518. 519. 520. 521. 522. 523. 524. 525. 526. 527. 528. 529. 530. 531. 532. 533. 534. 535. 536. 537. 538. 539. 540. 541. 542. 543. 544. 545. 546. 547. 548. 549. 550. 551. 552. 553. 554. 555. 556. 557. 558. 559. 560. 561. 562. 563. 564. 565. 566. 567. 568. 569. 570. 571. 572. 573. 574. 575. 576. 577. 578. 579. 580. 581. 582. 583. 584. 585. 586. 587. 588. 589. 590. 591. 592. 593. 594. 595. 596. 597. 598. 599. 600. 601. 602. 603. 604. 605. 606. 607. 608. 609. 610. 611. 612. 613. 614. 615. 616. 617. 618. 619. 620. 621. 622. 623. 624. 625. 626. 627. 628. 629. 630. 631. 632. 633. 634. 635. 636. 637. 638. 639. 640. 641. 642. 643. 644. 645. 646. 647. 648. 649. 650. 651. 652. 653. 654. 655. 656. 657. 658. 659. 660. 661. 662. 663. 664. 665. 666. 667. 668. 669. 670. 671. 672. 673. 674. 675. 676. 677. 678. 679. 680. 681. 682. 683. 684. 685. 686. 687. 688. 689. 690. 691. 692. 693. 694. 695. 696. 697. 698. 699. 700. 701. 702. 703. 704. 705. 706. 707. 708. 709. 710. 711. 712. 713. 714. 715. 716. 717. 718. 719. 720. 721. 722. 723. 724. 725. 726. 727. 728. 729. 730. 731. 732. 733. 734. 735. 736. 737. 738. 739. 740. 741. 742. 743. 744. 745. 746. 747. 748. 749. 750. 751. 752. 753. 754. 755. 756. 757. 758. 759. 760. 761. 762. 763. 764. 765. 766. 767. 768. 769. 770. 771. 772. 773. 774. 775. 776. 777. 778. 779. 780. 781. 782. 783. 784. 785. 786. 787. 788. 789. 790. 791. 792. 793. 794. 795. 796. 797. 798. 799. 800. 801. 802. 803. 804. 805. 806. 807. 808. 809. 810. 811. 812. 813. 814. 815. 816. 817. 818. 819. 820. 821. 822. 823. 824. 825. 826. 827. 828. 829. 830. 831. 832. 833. 834. 835. 836. 837. 838. 839. 840. 841. 842. 843. 844. 845. 846. 847

CONSTRAINTS THIS FAR

1. PLATE TECTONICS
2. NON-ELASTIC CREEP RHEOLOGY
3. BRITTLE (ELASTIC) FRACTURE
4. GEOMETRY OF FRACTURE SURFACES & ORIENTATIONS

Summary of Lecture 2

1. Three time scales of seismic phenomena

- To analyse seismogram in a given period range, we should have a good model of the source in that period range
- What causes the time delays in aftershocks?

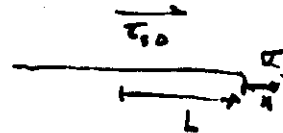
2. Creep phenomena in laboratory expts.

- Water saturated rocks creep before they break.
- Accelerated creep prior to fracture
- Time delays to fracture decrease with increasing external stress

$$t_R \sim e^{-(\sigma_{ext}/T)/const}$$

3. Increasing fracture (earthquake) size of foreshocks prior to Main Shock.

- Explanation of seismic gaps & droughts
- Stress redistribution upon fracture



$$\sigma \sim \frac{\sigma_0 \sqrt{L}}{\sqrt{x}} \quad \text{short range}$$

$$\sim \sigma_0 \frac{L^2}{x^2} \quad \text{long range}$$

brakside

$$\sigma = \sigma_0$$

c. Crack Fusion!

4. Anisotropy, multiple fractures in large shocks

- Solution in water of polycrystalline rocks & recrystallization

5. Low viscosity zone in lower crust (low-diff trans. what?)

- Ductility (plasticity) of lower crust: brittle-ductile transition

