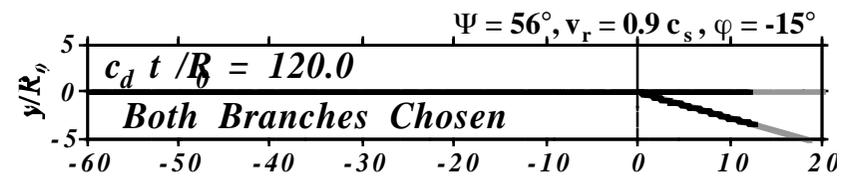
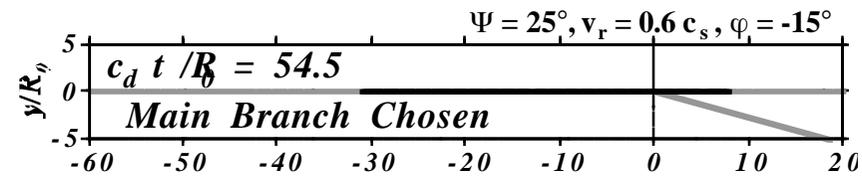
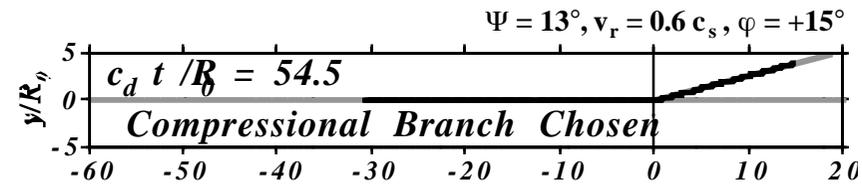
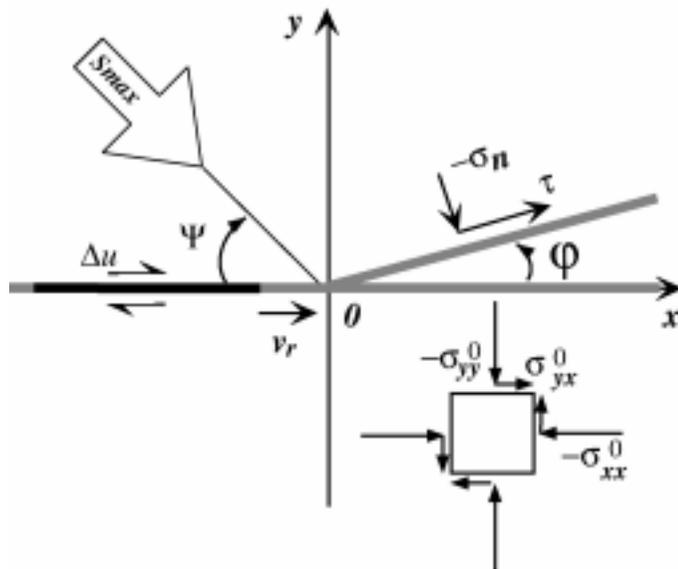


動的モデルによる分岐断層上の破壊伝播

-初期応力場と波動応力場の効果-

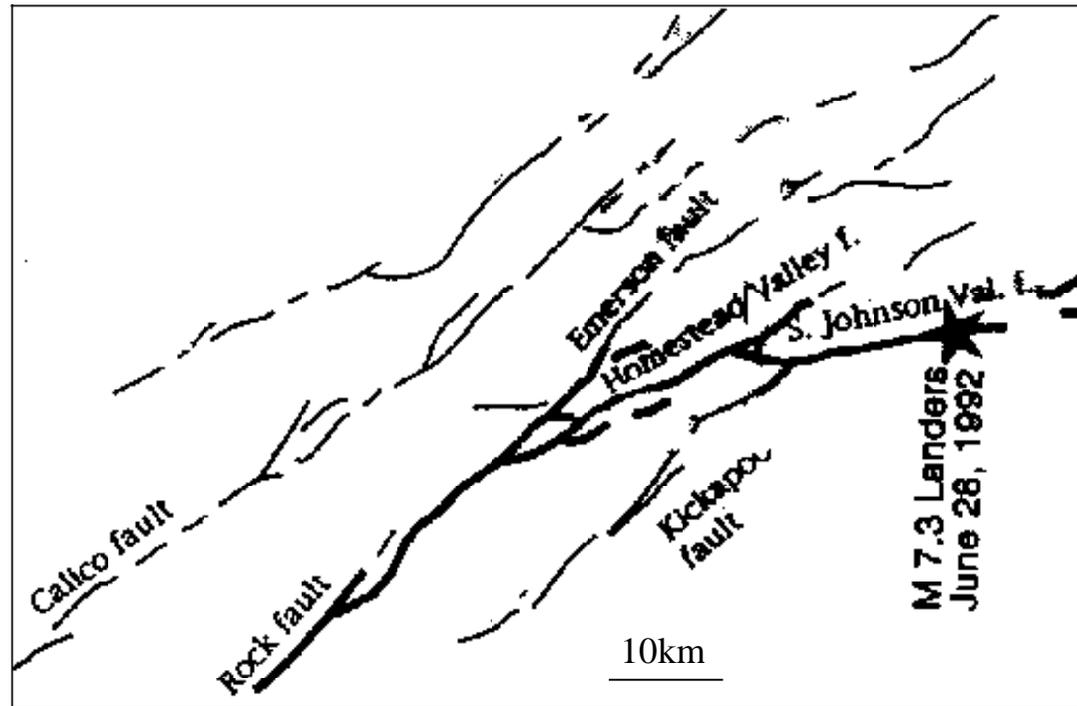
Effects of pre-stress state and rupture velocity on dynamic fault branching



九州大学 大学院理学研究院

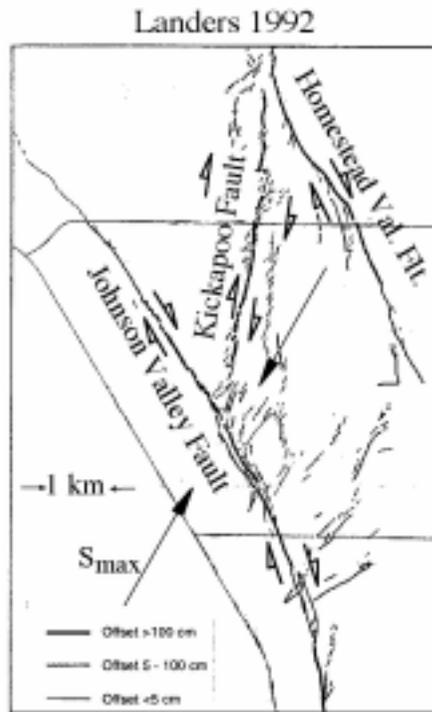
亀 伸樹

研究の背景

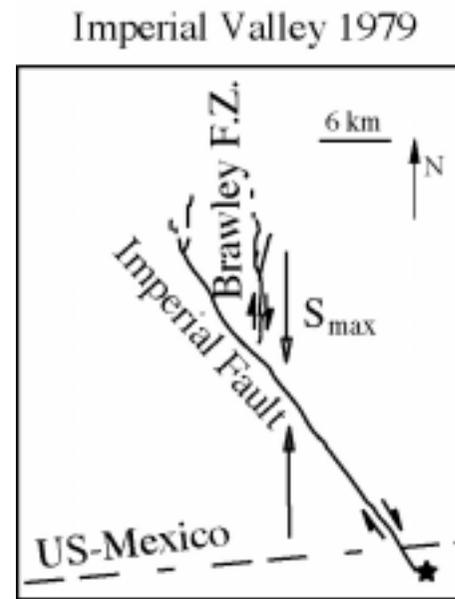


- 幾何的複雑さ：分岐、屈曲、飛びの構造
- 破壊経路の予測 地震危険度評価

分岐断層(Strike Slip Type)



(Sowers et al., 1994)

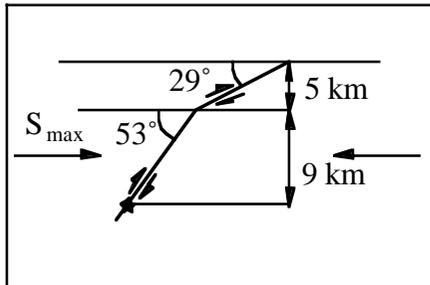


(Archuleta., 1984)

- 動的に破壊分岐

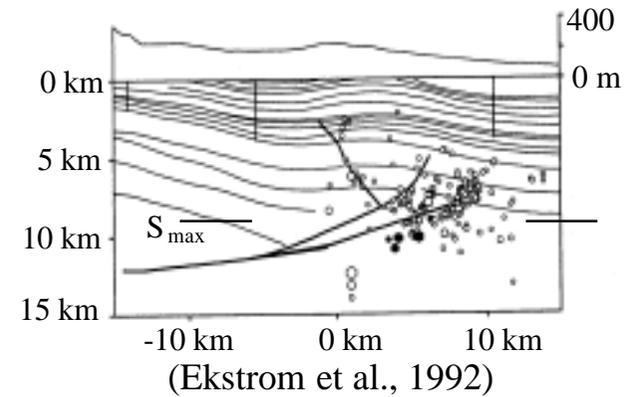
分岐断層 (Thrust Type)

San Fernando 1971



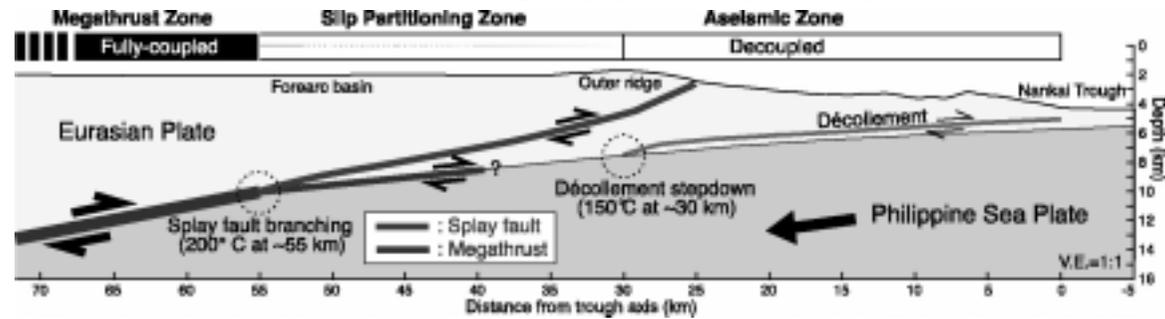
(Heaton & Helmberger, 1979)

Kettleman Hills 1985



(Ekstrom et al., 1992)

Nankai Subduction Zone



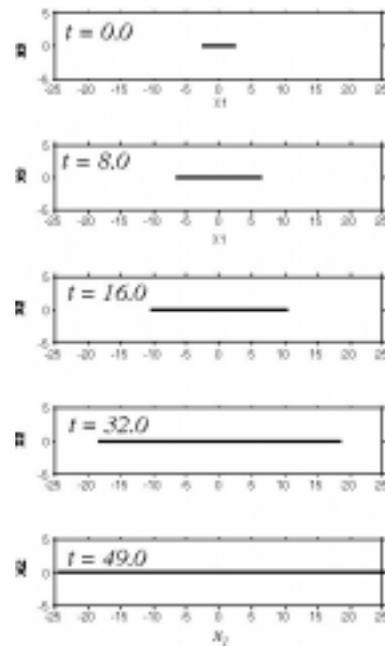
(Park et al., 2002)

動的に分岐したかは不明

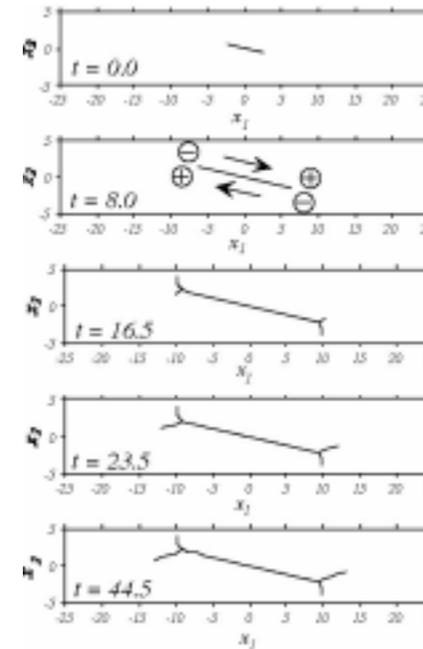
研究の背景（計算手法編）

- 境界積分方程式法(Boundary Integral Equation Method)の発展
形上に制約のない動的破壊計算が可能になった

制約のある「まっすぐ」破壊



制約のない破壊シミュレーション



(Kame and Yamashita, 1999a, 1999b, 2002)

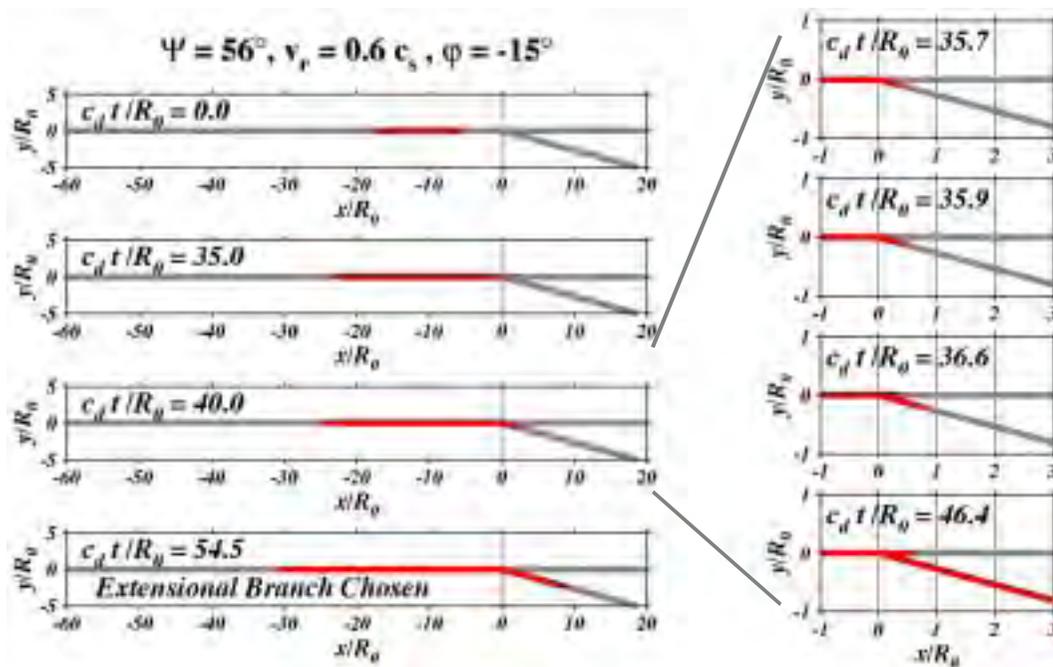
破壊面の形状と動的破壊過程との関係に注目が集まる

研究の目的

動的モデルによる分岐断層上の破壊伝播シミュレーション

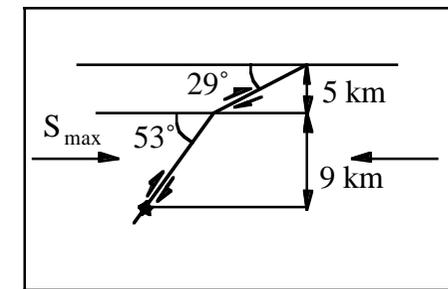
⇒ 破壊経路選択の力学の理解

⇒ 現実の地震破壊経路の解釈



破壊伝播シミュレーション

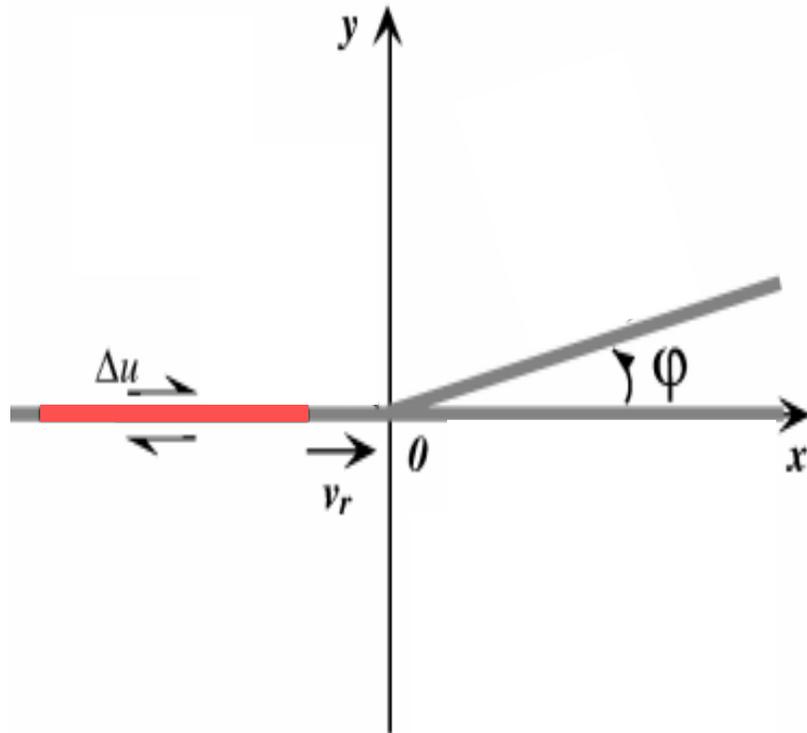
San Fernando 1971



(Heaton & Helmberger, 1979)

現実の地震破壊経路

考える分岐断層モデル

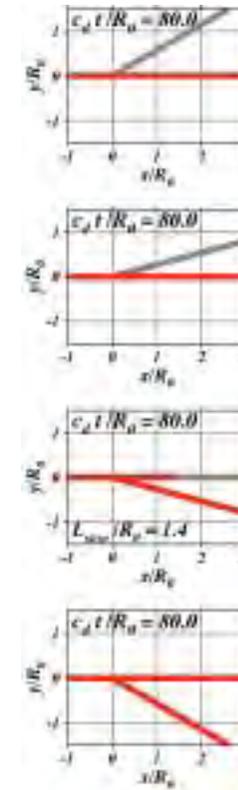
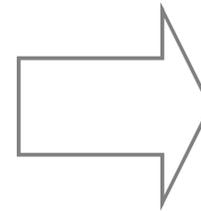
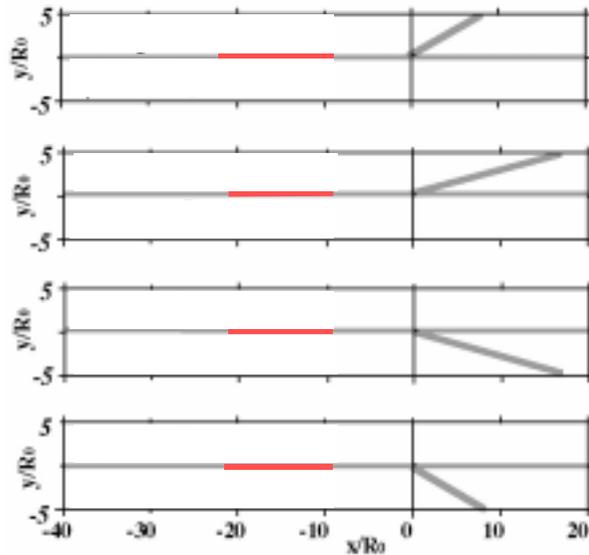


破壊が直線主断層上を伝播している



破壊が交点で分岐断層と出会う

分岐断層上での破壊選択は？



?

?

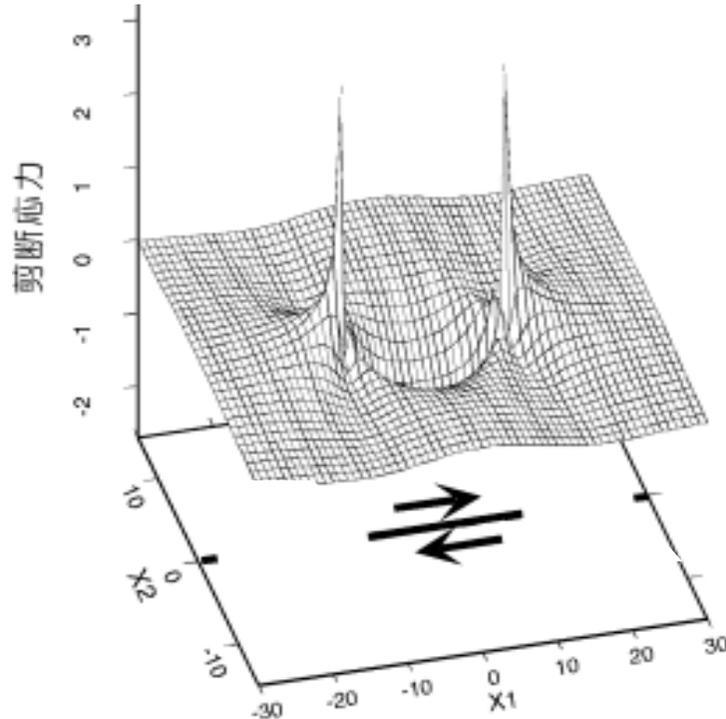
?

?

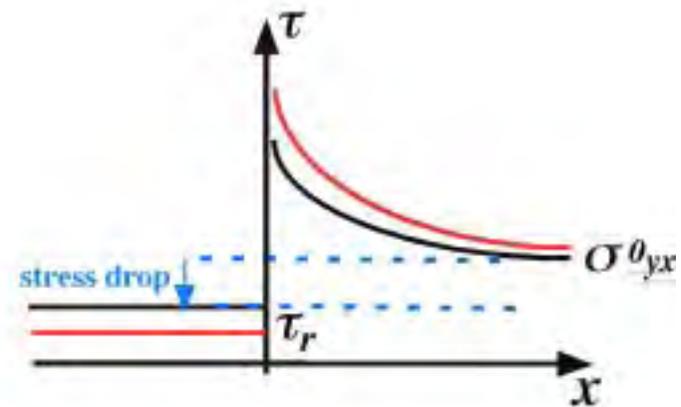
- 分岐断層は破壊するのか？
- 破壊しやすい分岐断層はどちら側か？
- 主断層上の破壊は止まるのか？
- 最終的な破壊経路は？

破壊の力学 1

- 地震：弾性体中のせん断亀裂としてモデル化
- 動力学モデル 破壊の先端の応力も注目



せん断亀裂が作り出す応力場



Stress drop 小 応力集中小
Stress drop 大 応力集中大

Stress drop : エネルギーの供給源 成長継続の要素

破壊の力学 2

- 破壊進展の記述：Slip-weakening Coulomb Law
- 破壊強度 τ_p を越える 破壊の進展

動的モデルにおける破壊経路の選択手順

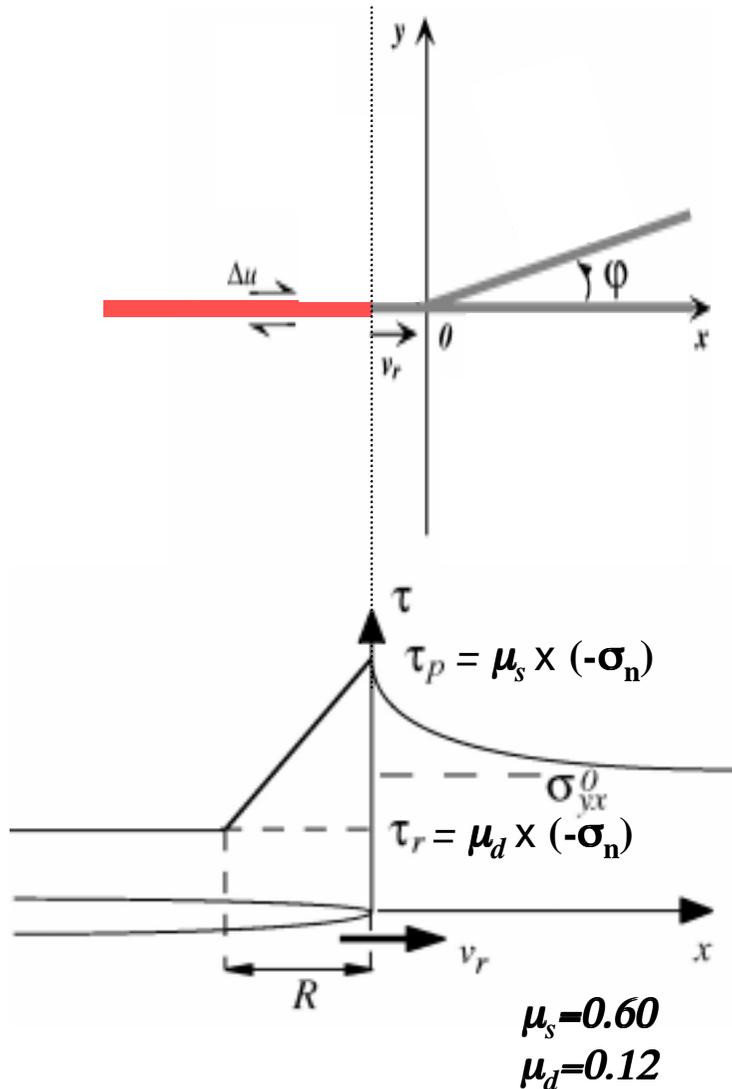
直線主断層上

先端の応力で破壊の進展を判定

分岐断層上

分岐点根本の応力で破壊開始を判定
先端の応力で破壊の進展を判定

Stress drop, peak stress, normal stress dependent
R0: unit length

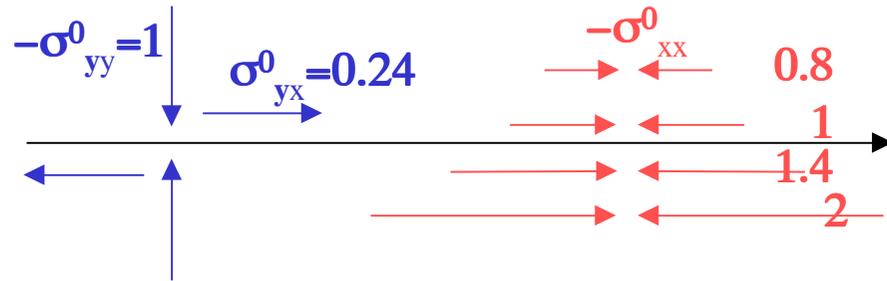
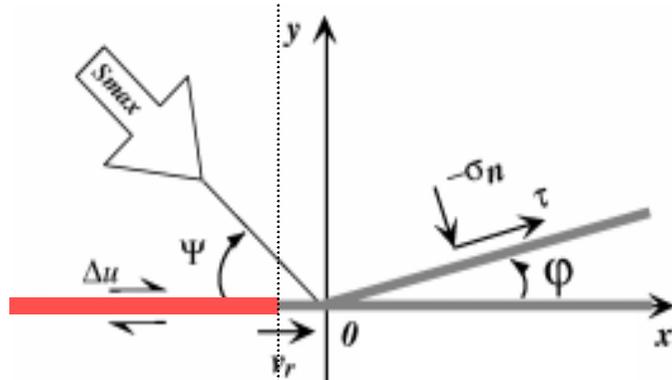


OnとOff：対照実験の為のパラメタ選択

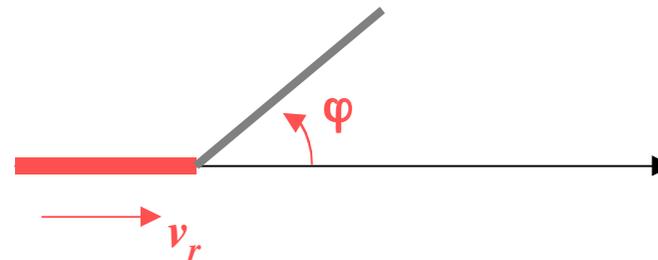
(1) 初期応力場主軸 S_{max} の角度 Ψ

On-planeの条件を固定して

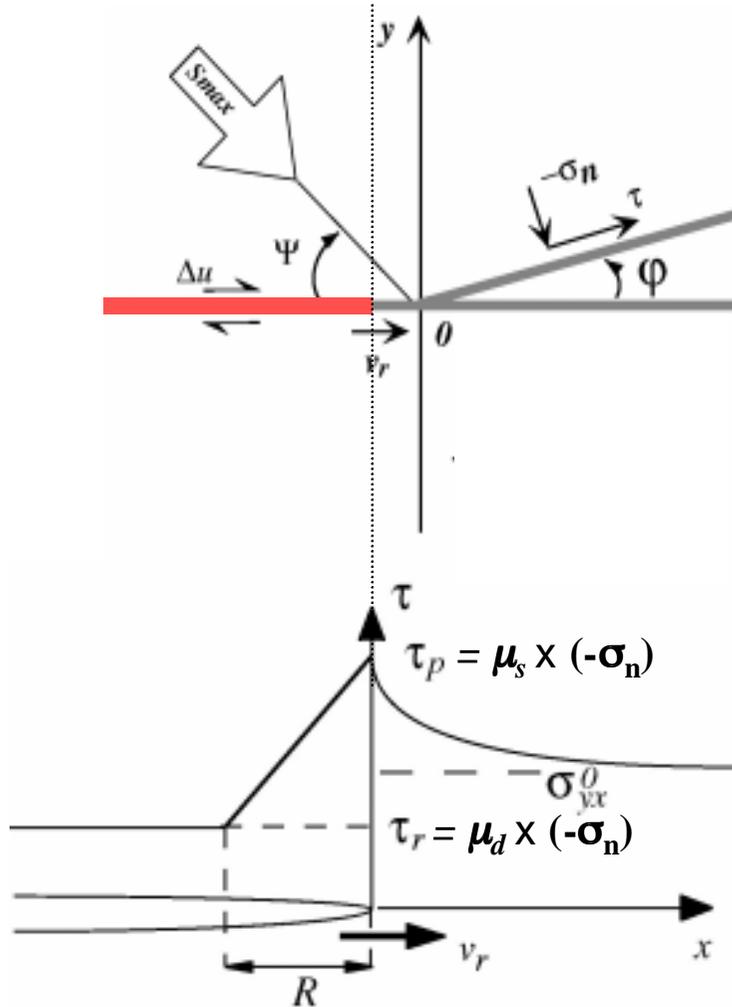
Off-planeの応力状態を σ_{xx}^0 で変化させる



(2) 分岐断層の角度： φ



(3) 分岐点に進入する時の破壊速度： v_r



分岐断層面が存在しない場合には、主断層上で同じ破壊履歴になるようになっている

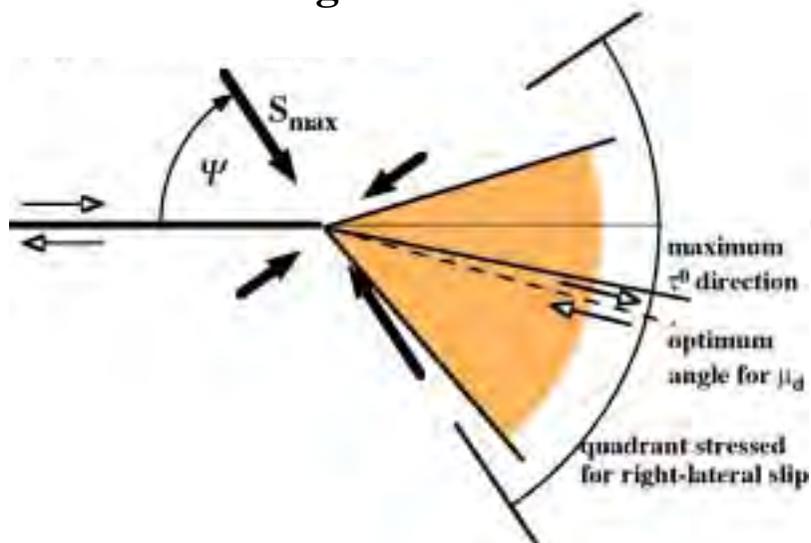
Off-plane Factor 1

- 初期応力場の効果
: 最大主軸の角度 Ψ

⇒ Stress dropの最適方向

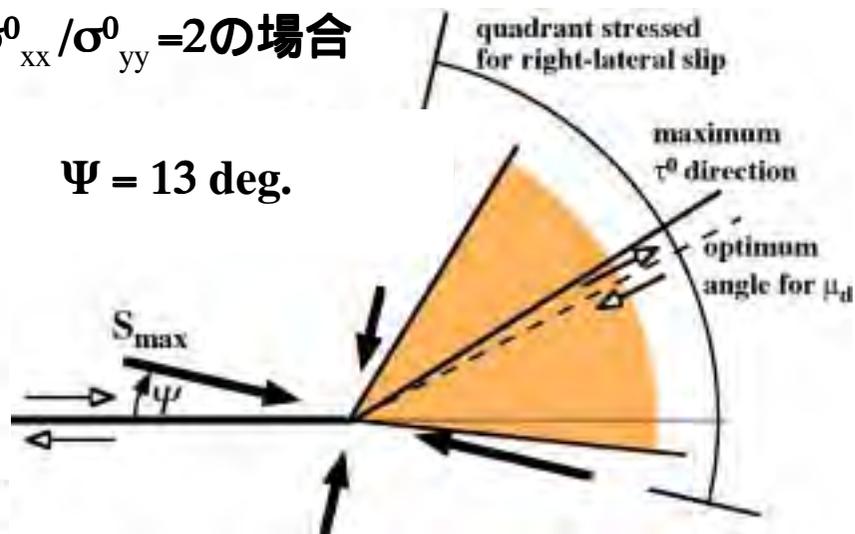
$\sigma_{xx}^0 / \sigma_{yy}^0 = 0.8$ の場合

$\Psi = 56$ deg.



$\sigma_{xx}^0 / \sigma_{yy}^0 = 2$ の場合

$\Psi = 13$ deg.



図：Stress drop 正の範囲と最適面の方向
(破壊により生じる応力を含まない考察)

Off-plane Factor 2

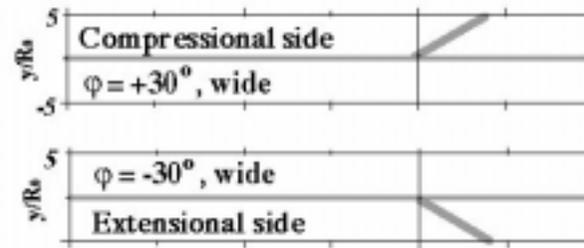
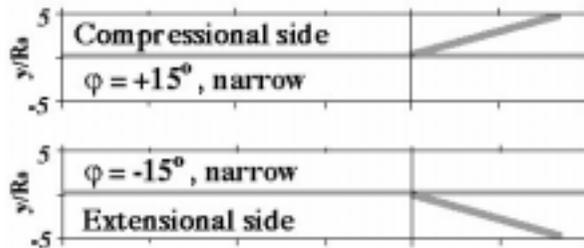
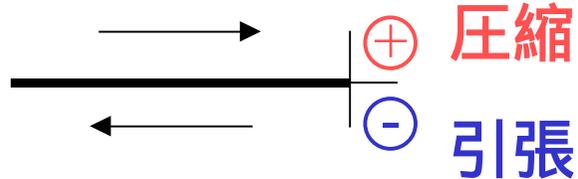
- 分岐角度： φ

角度が小さいと同時成長が困難

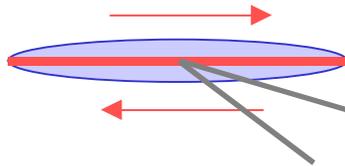
$\varphi > 0$: 圧縮側 : 破壊しにくくなる

$\varphi < 0$: 引張側 : 破壊しやすくなる

右ずれ滑りによる破壊先端の押引



破壊により生じるStress Shadow

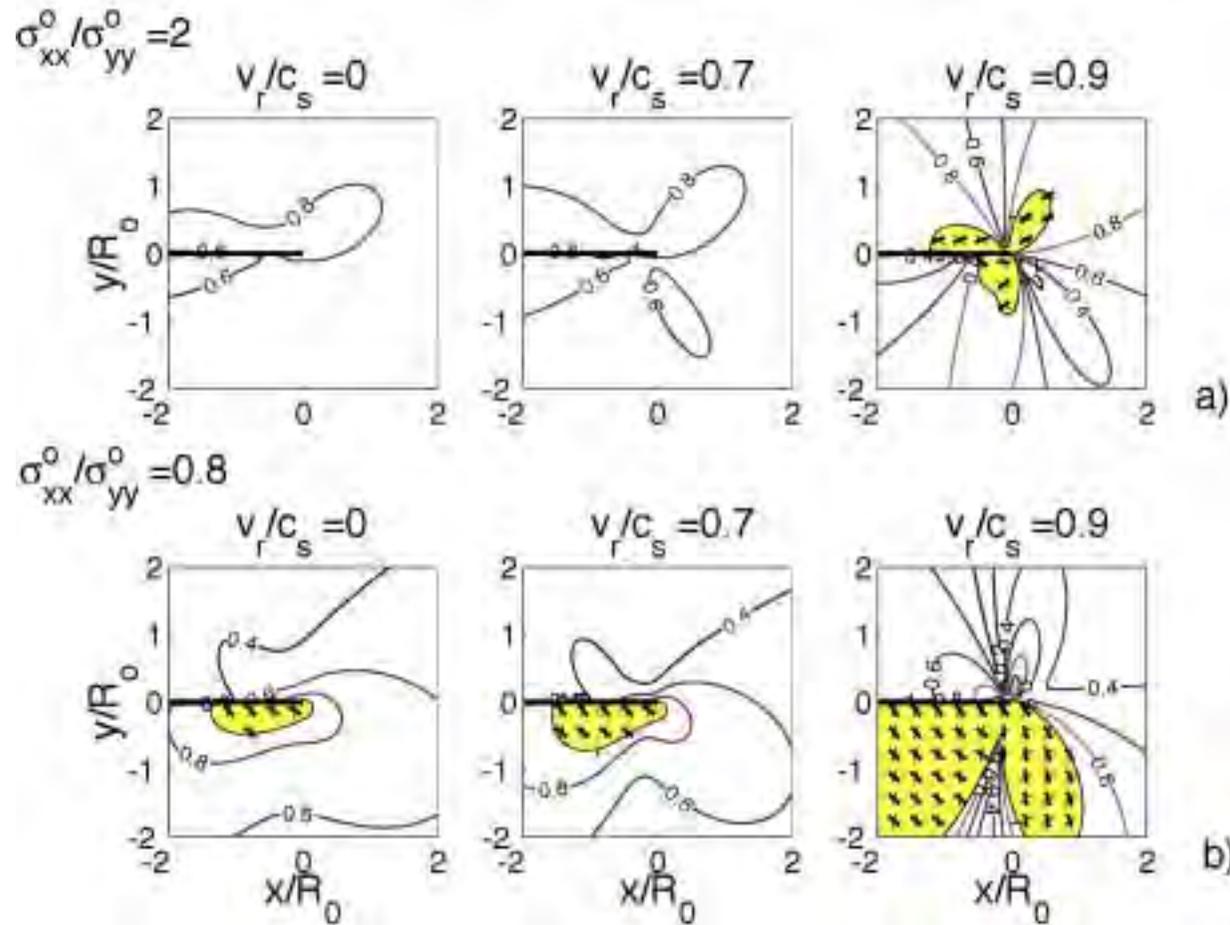


角度が小さいと同時成長が困難

(初期応力は入っていない考察)

Off-plane Factor 3

- 破壊速度の大：波動応力場の卓越

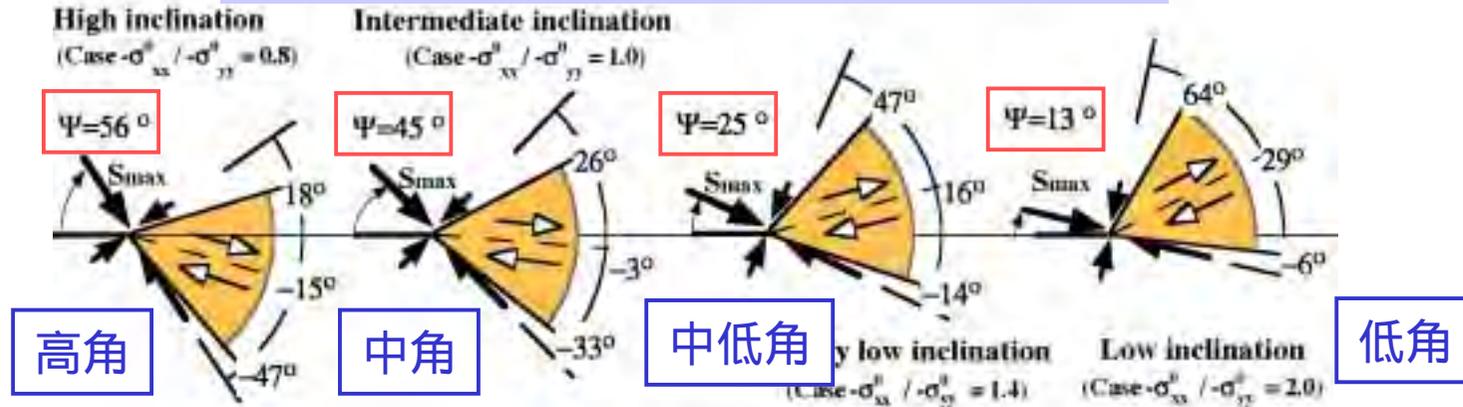


SWする破壊先端周辺のクーロン応力分布

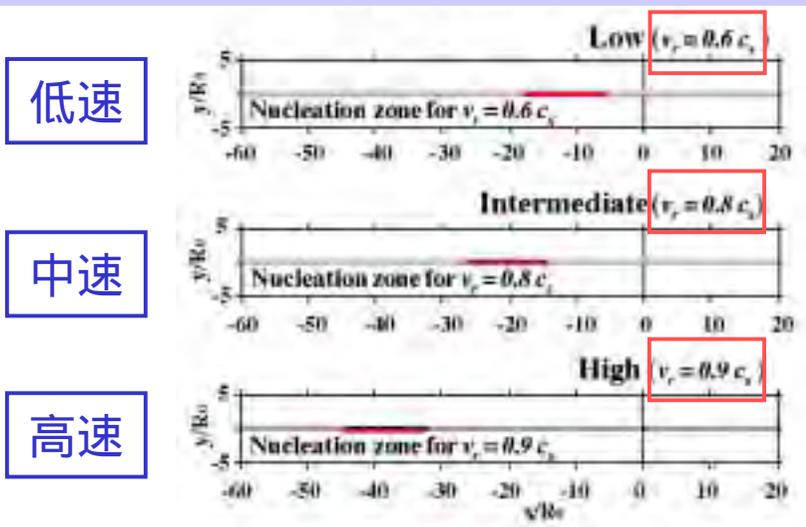
(分岐断層面上の破壊による応力を含まない考察)

3つのパラメタ

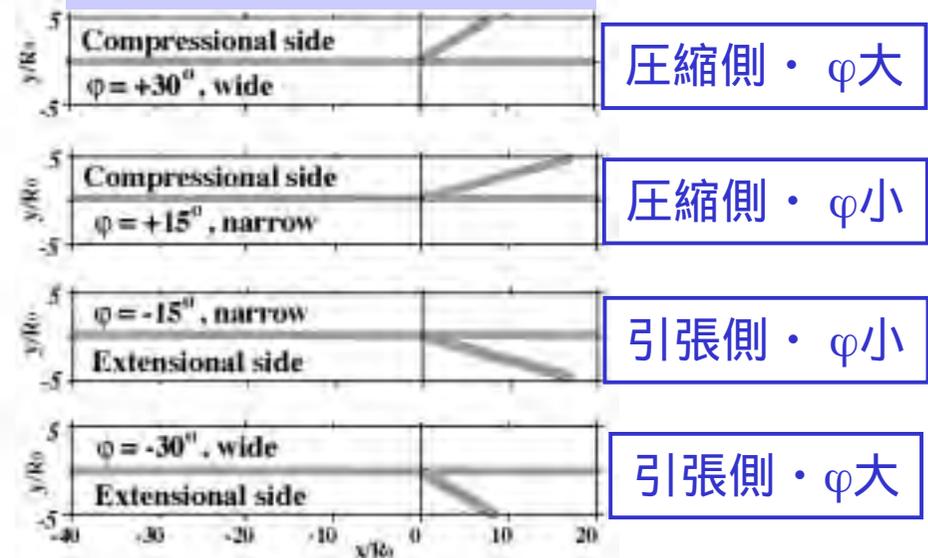
(1) 初期応力場：最大圧縮主軸 S_{max} の角度 Ψ



(2) 分岐点に進入する時の破壊速度： v_r



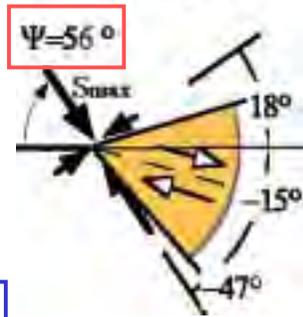
(3) 分岐断層の角度： φ



- 48のパラメタ組み合わせを網羅的に調べる

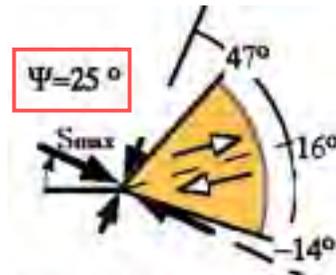
対照実験 1 : 初期応力場の効果

High inclination
(Case $-\sigma_{xx}^0 / -\sigma_{yy}^0 = 0.8$)



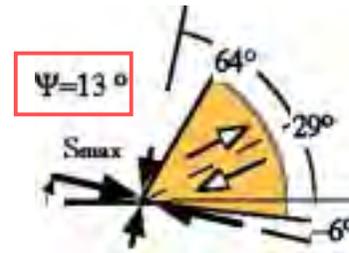
高角

$\Psi = 56^\circ, v_r = 0.6 c_s, \varphi = -15^\circ$



中低角

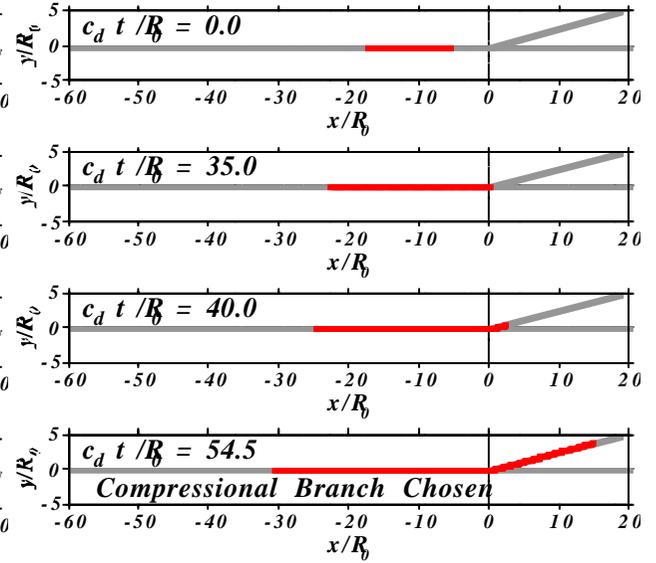
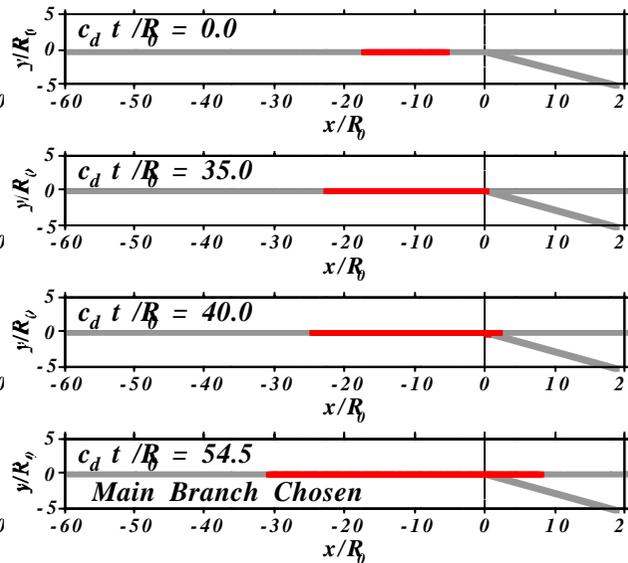
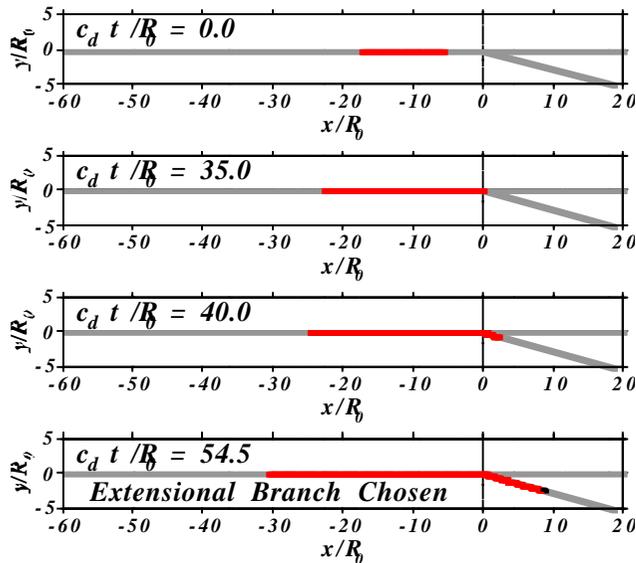
$\Psi = 25^\circ, v_r = 0.6 c_s, \varphi = -15^\circ$



低角

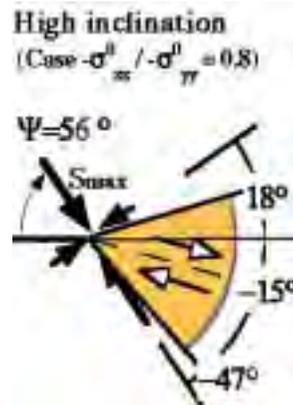
Low inclination
(Case $-\sigma_{xx}^0 / -\sigma_{yy}^0 = 2$)

$\Psi = 13^\circ, v_r = 0.6 c_s, \varphi = +15^\circ$



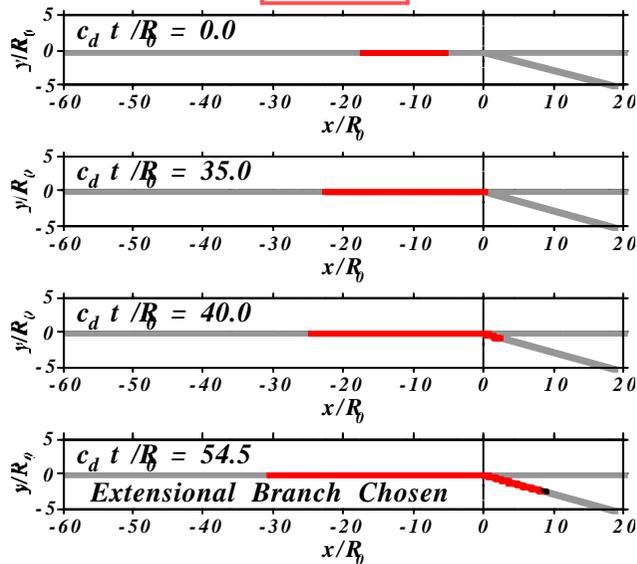
- 選択される破壊経路が引張側から圧縮側へ移行
- 他方の破壊は停止する Stress shadow効果

対照実験 2 : 分岐点に進入時の破壊速度の効果



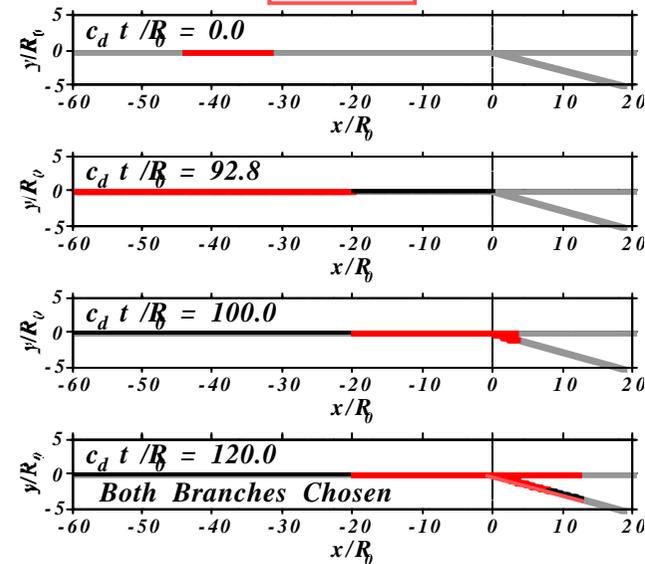
破壊速度 : 低速

$\Psi = 56^\circ$, $v_r = 0.6 c_s$, $\varphi = -15^\circ$



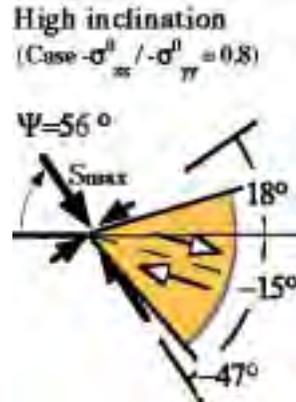
破壊速度 : 高速

$\Psi = 56^\circ$, $v_r = 0.9 c_s$, $\varphi = -15^\circ$



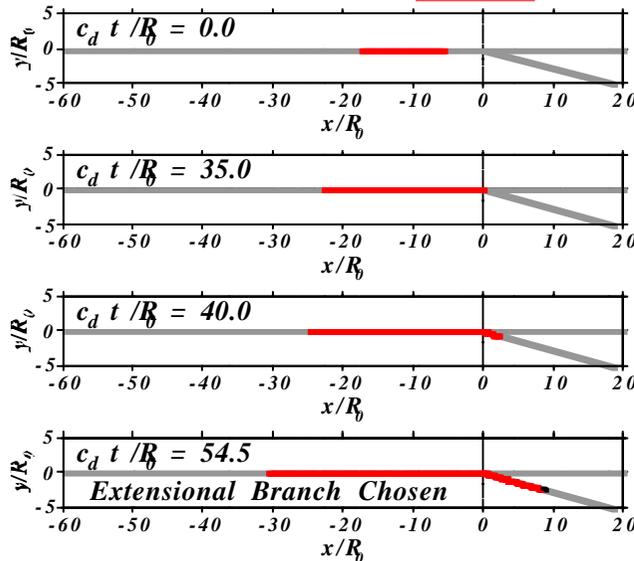
- 分岐点に進入する時の破壊速度が大きくなると両断層面上の同時破壊が可能になる

対照実験 3 : 分岐角度の効果



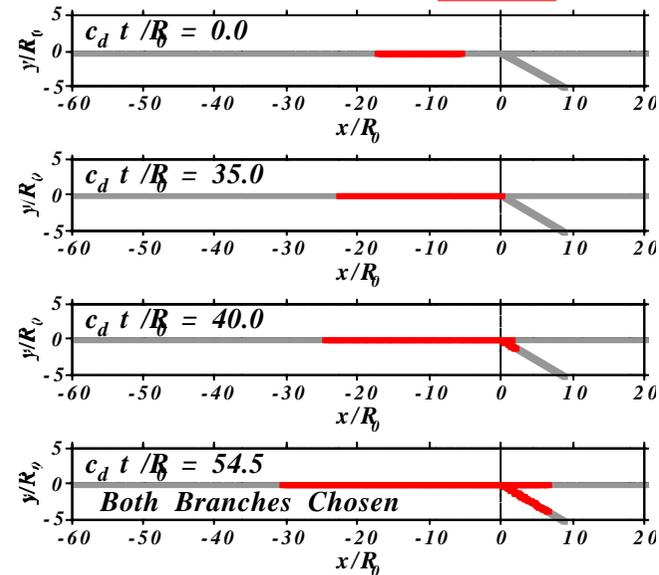
分岐角：小

$$v_r = 0.6 c_s, \varphi = -15^\circ$$



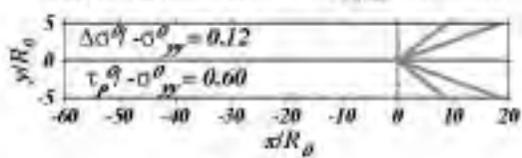
分岐角：大

$$v_r = 0.6 c_s, \varphi = -30^\circ$$



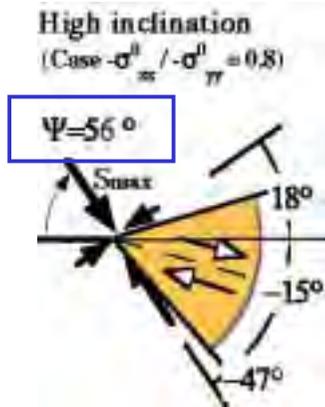
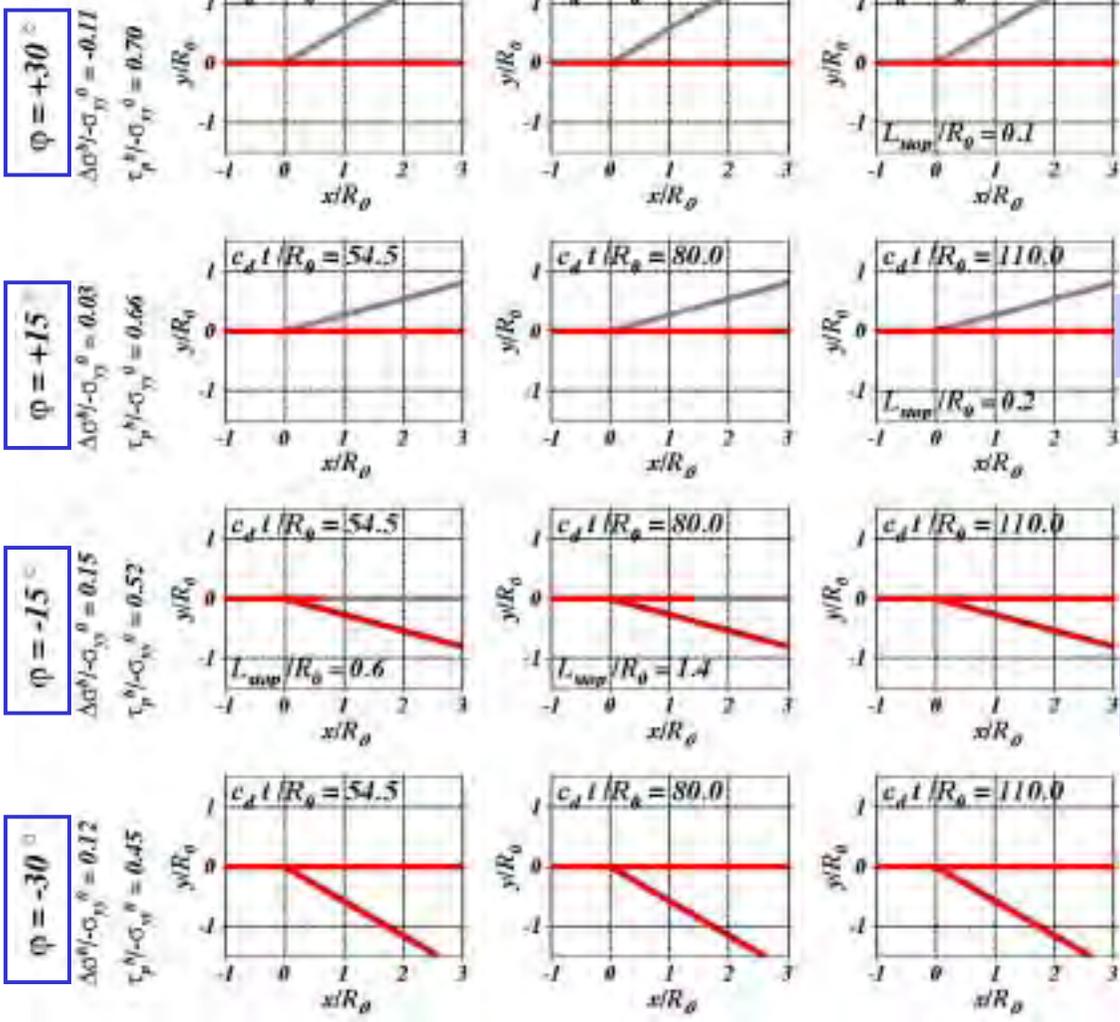
- 分岐角度大 相互作用小 両断層面上の同時破壊が可能になる

High Inclination of S_{max} , $\Psi = 56^\circ$



S_{max} , $\Psi = 56\text{deg.}$ の最終破壊経路

$v_r = 0.6 c_s$ $v_r = 0.8 c_s$ $v_r = 0.9 c_s$



Stress drop最適面

圧縮側分岐断層 破壊選択されない

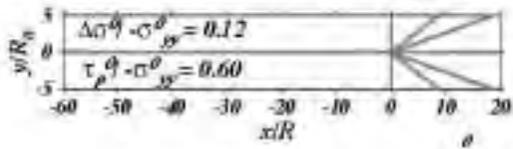
τ_{peak} 大
Stress drop 小, or 負
動的破壊励起可能

引張側分岐断層 破壊選択される

破壊速度大で両破壊
分岐角大で両破壊

Intermediate Inclination of S_{max} , $\Psi = 45^\circ$

S_{max} , $\Psi = 45^\circ$ の最終破壊経路



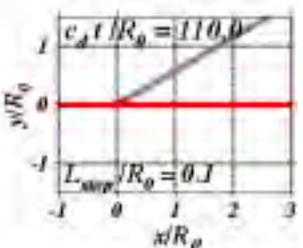
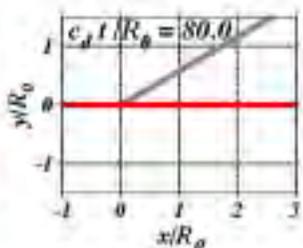
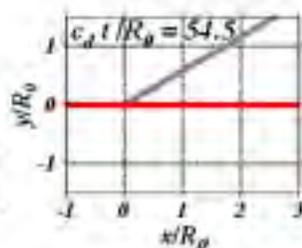
$v_r = 0.6 c_s$

$v_r = 0.8 c_s$

$v_r = 0.9 c_s$

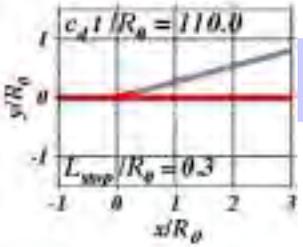
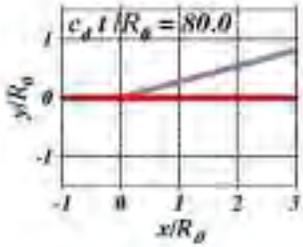
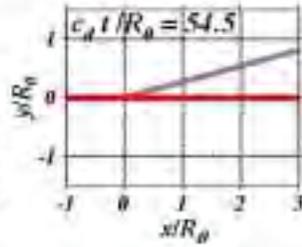
$\varphi = +30^\circ$

$\Delta\sigma^{\theta} - \sigma^{\theta}_{yy} = -0.03$
 $\tau_p^{\theta} - \sigma^{\theta}_{yy} = 0.73$



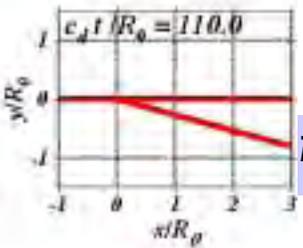
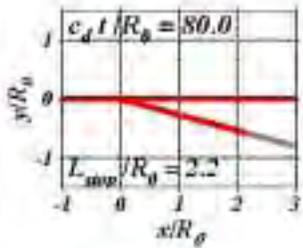
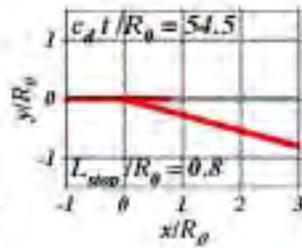
$\varphi = +15^\circ$

$\Delta\sigma^{\theta} - \sigma^{\theta}_{yy} = 0.07$
 $\tau_p^{\theta} - \sigma^{\theta}_{yy} = 0.67$



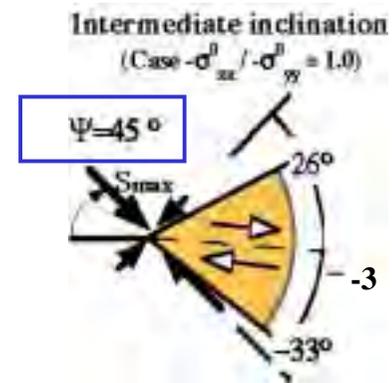
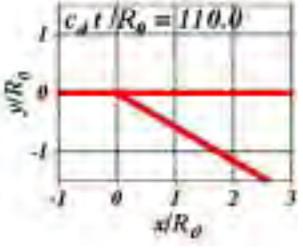
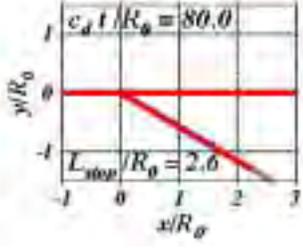
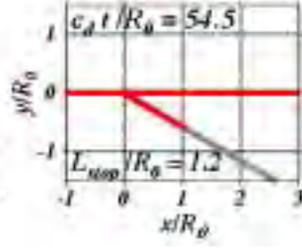
$\varphi = -15^\circ$

$\Delta\sigma^{\theta} - \sigma^{\theta}_{yy} = 0.10$
 $\tau_p^{\theta} - \sigma^{\theta}_{yy} = 0.53$



$\varphi = -30^\circ$

$\Delta\sigma^{\theta} - \sigma^{\theta}_{yy} = 0.03$
 $\tau_p^{\theta} - \sigma^{\theta}_{yy} = 0.48$



-3 Stress drop最適面

圧縮側分岐断層

破壊選択されない

τ_{peak} 大
Stress drop 小, or 負
動的破壊励起可能

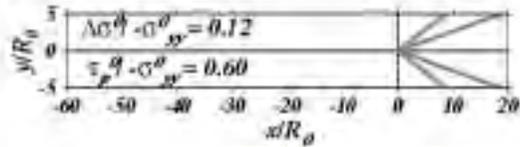
引張側分岐断層

破壊選択可能

破壊速度大で両破壊
-30deg. は途中で止まる

Intermediately Low Inclination of S_{max} , $\Psi = 25^\circ$

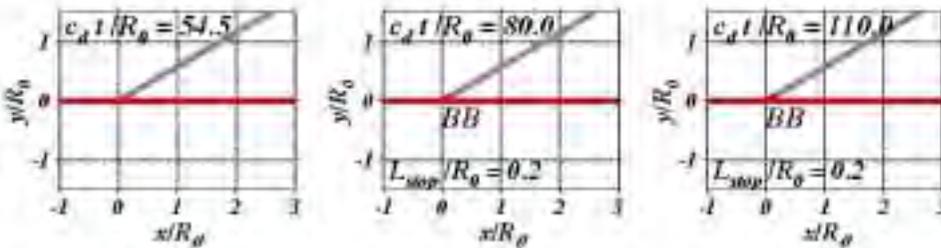
S_{max} , $\Psi = 25^\circ$ の最終破壊経路



$v_r = 0.6 c_s$ $v_r = 0.8 c_s$ $v_r = 0.9 c_s$

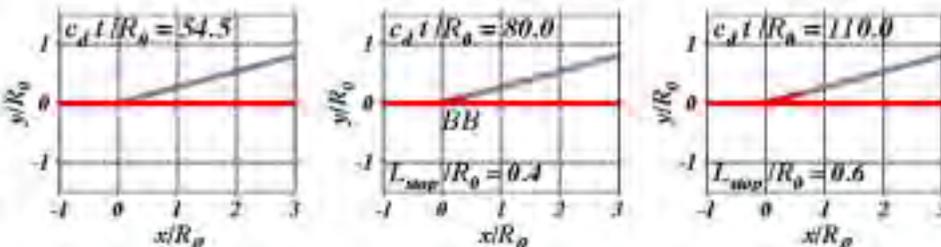
$\varphi = +30^\circ$

$\Delta\sigma^0_x - \sigma^0_{yy} = 0.14$
 $\tau^0_{xy} - \sigma^0_{yy} = 0.79$



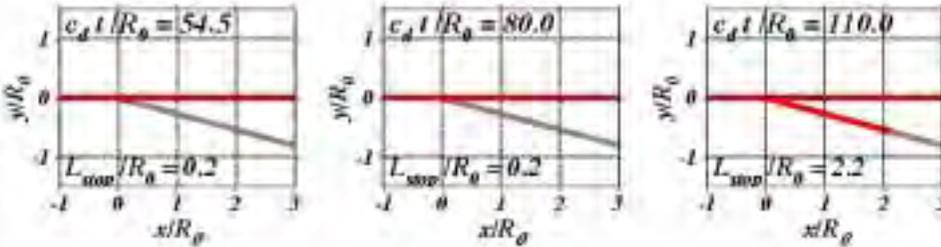
$\varphi = +15^\circ$

$\Delta\sigma^0_x - \sigma^0_{yy} = 0.17$
 $\tau^0_{xy} - \sigma^0_{yy} = 0.69$



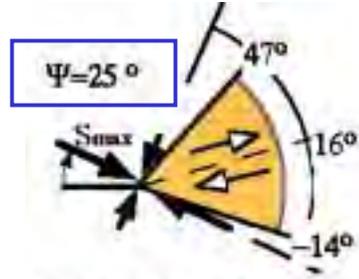
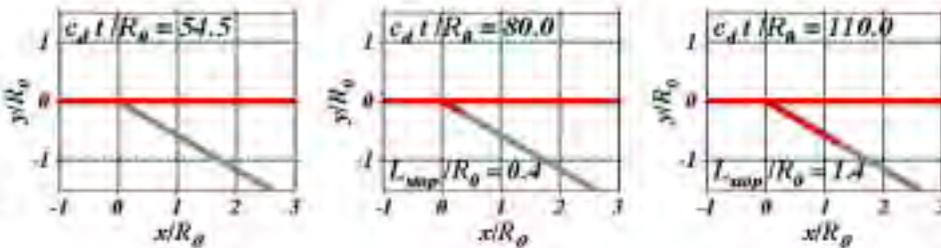
$\varphi = -15^\circ$

$\Delta\sigma^0_x - \sigma^0_{yy} = -0.09$
 $\tau^0_{xy} - \sigma^0_{yy} = 0.54$



$\varphi = -30^\circ$

$\Delta\sigma^0_x - \sigma^0_{yy} = -0.16$
 $\tau^0_{xy} - \sigma^0_{yy} = 0.54$



stress drop最適面

圧縮側分岐断層 破壊選択されない

τ_{peak} 大

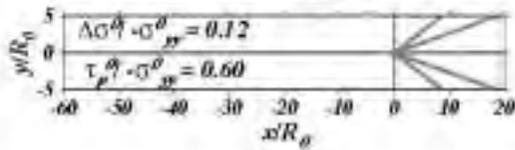
後方破壊励起発生
Branching Behind

引張側分岐断層 破壊選択されない

stress drop 負

動的に励起されるのみ

Low Inclination of S_{max} , $\Psi = 13^\circ$

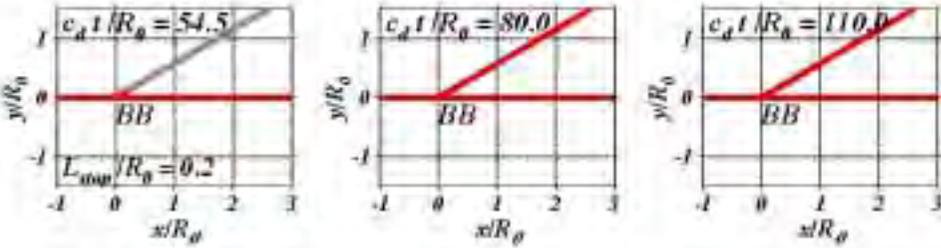


S_{max} , $\Psi = 13\text{deg.}$ の最終破壊経路

$v_r = 0.6 c_s$ $v_r = 0.8 c_s$ $v_r = 0.9 c_s$

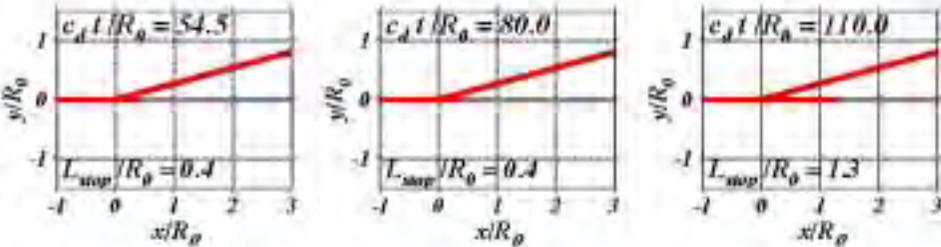
$\varphi = +30^\circ$

$\Delta\sigma^{\theta} - \sigma_{yy}^{\theta} = 0.38$
 $\tau_p^{\theta} - \sigma_{yy}^{\theta} = 0.88$



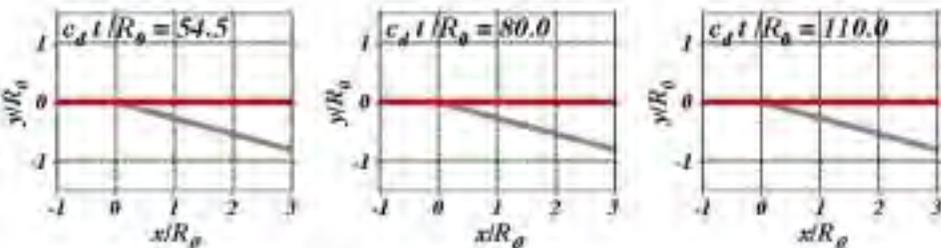
$\varphi = +15^\circ$

$\Delta\sigma^{\theta} - \sigma_{yy}^{\theta} = 0.31$
 $\tau_p^{\theta} - \sigma_{yy}^{\theta} = 0.71$



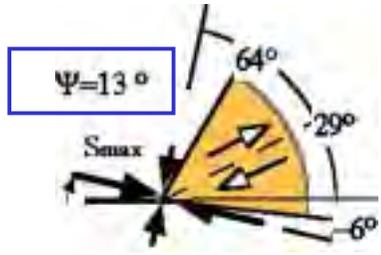
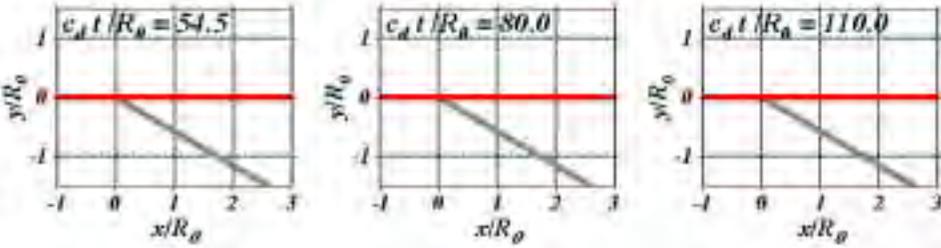
$\varphi = -15^\circ$

$\Delta\sigma^{\theta} - \sigma_{yy}^{\theta} = -0.16$
 $\tau_p^{\theta} - \sigma_{yy}^{\theta} = 0.57$



$\varphi = -30^\circ$

$\Delta\sigma^{\theta} - \sigma_{yy}^{\theta} = -0.44$
 $\tau_p^{\theta} - \sigma_{yy}^{\theta} = 0.63$



stress drop最適面

圧縮側分岐断層 破壊選択される

τ_{peak} 大, but stress drop 大

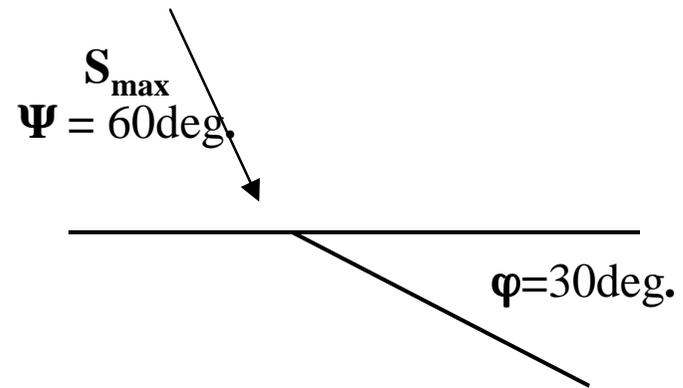
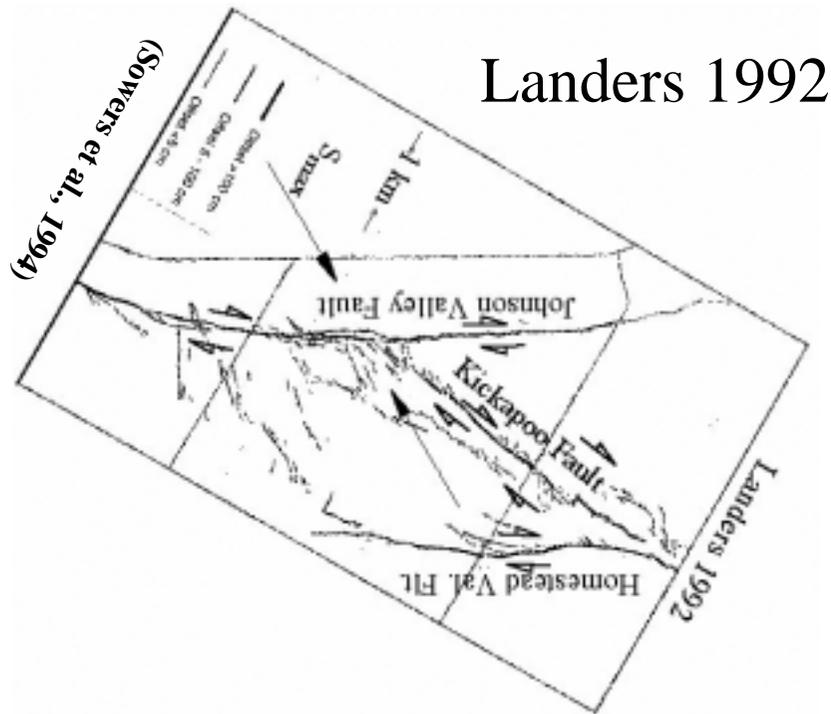
後方破壊励起発生 (Branching Behind)

破壊速度大で両破壊

引張側分岐断層 破壊選択されない

シミュレーション結果は
実際の地震破壊面と調和的か？

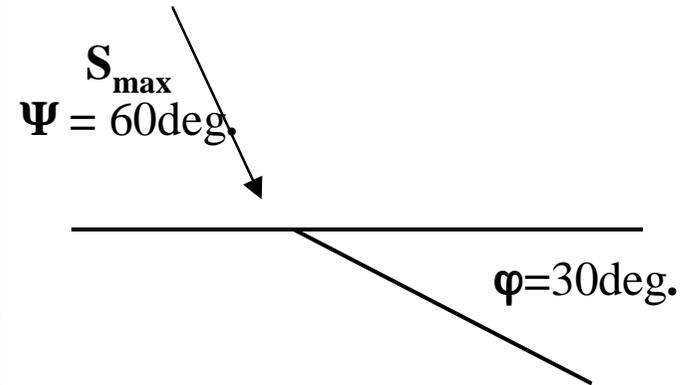
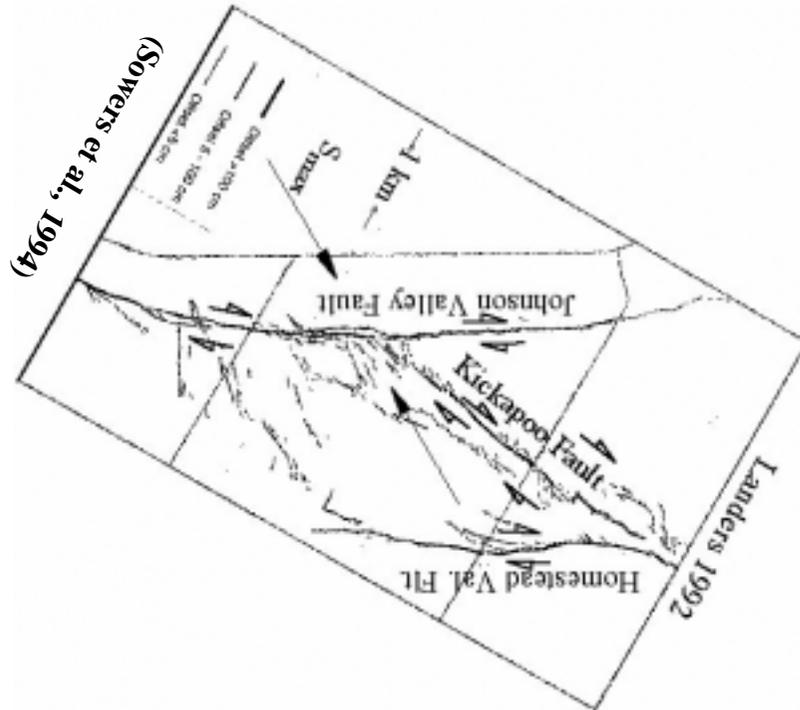
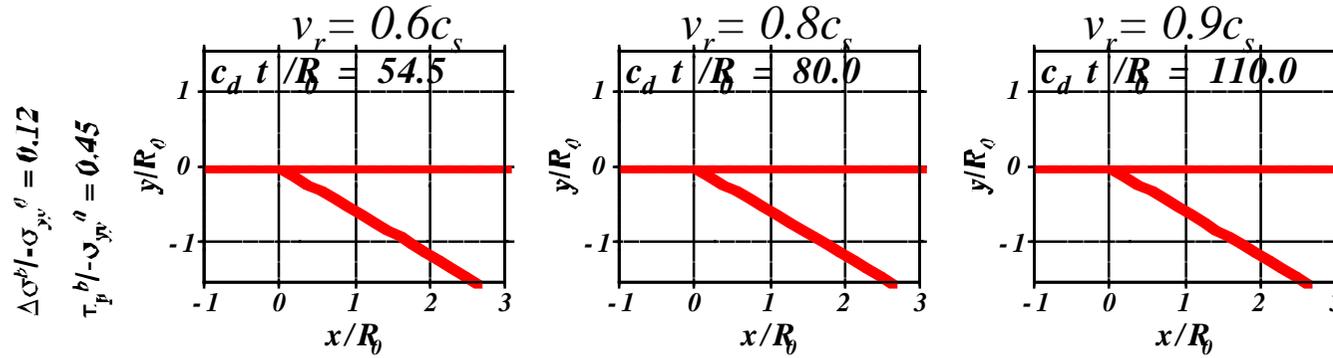
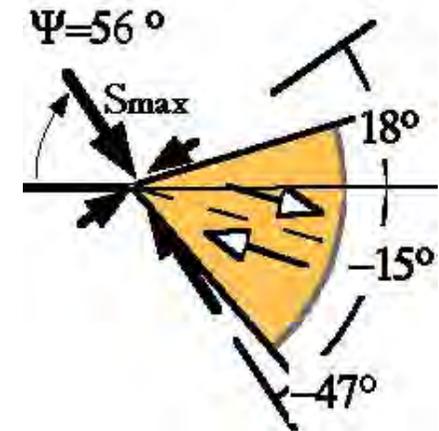
- 応力主軸の向き \Leftrightarrow 破壊選択方向



(Hardebeck and Hauksson, 2001)

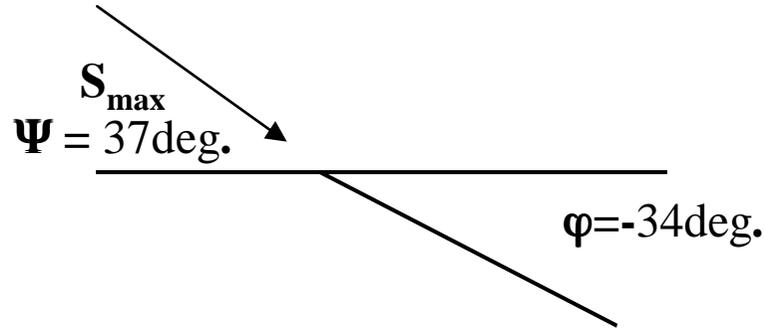
Landers 1992 (Strike Slip Type)

High inclination
(Case $-\sigma_{xx}^0 / -\sigma_{yy}^0 = 0.8$)

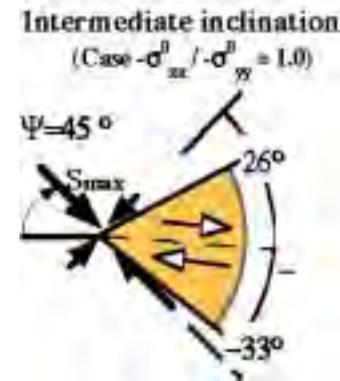


(Hardebeck and Hauksson, 2001)

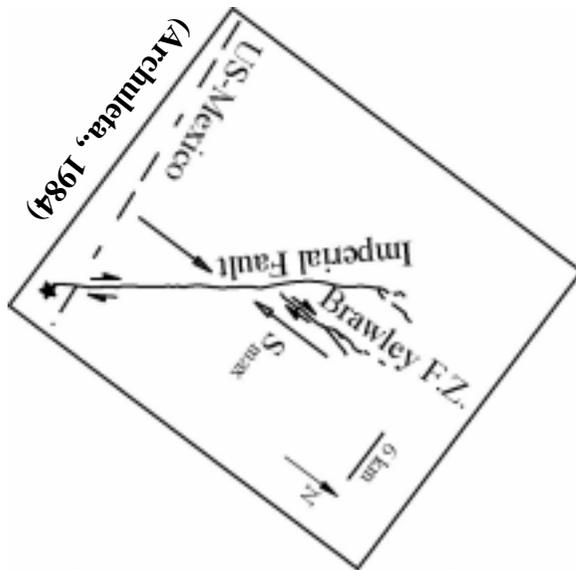
Imperial Valley 1979 (Strike Slip Type)



(Hardebeck and Hauksson, 1999)

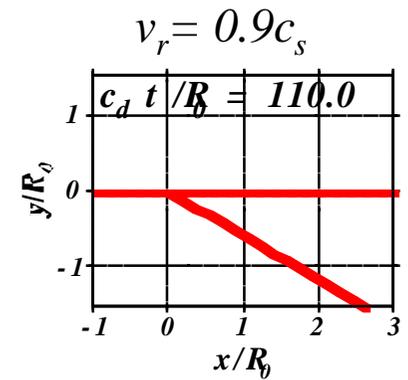
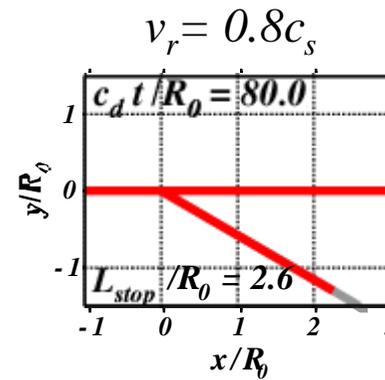
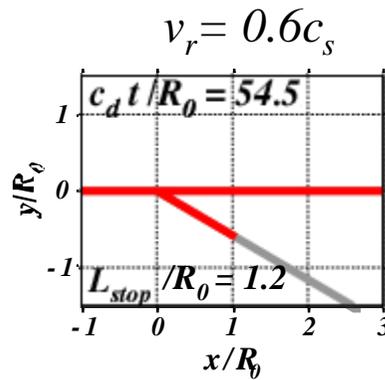


$\varphi = -30\text{deg.}$



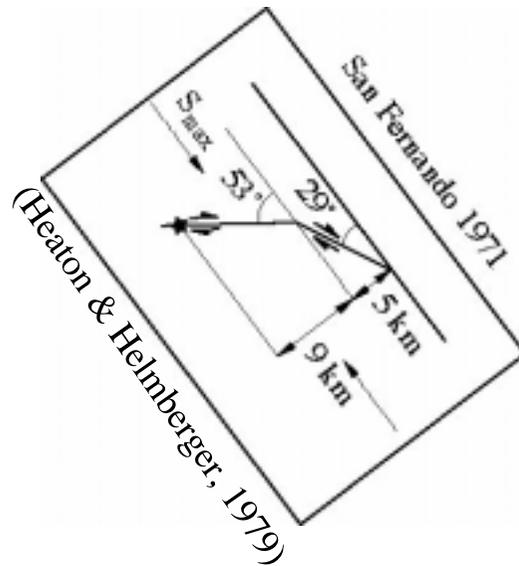
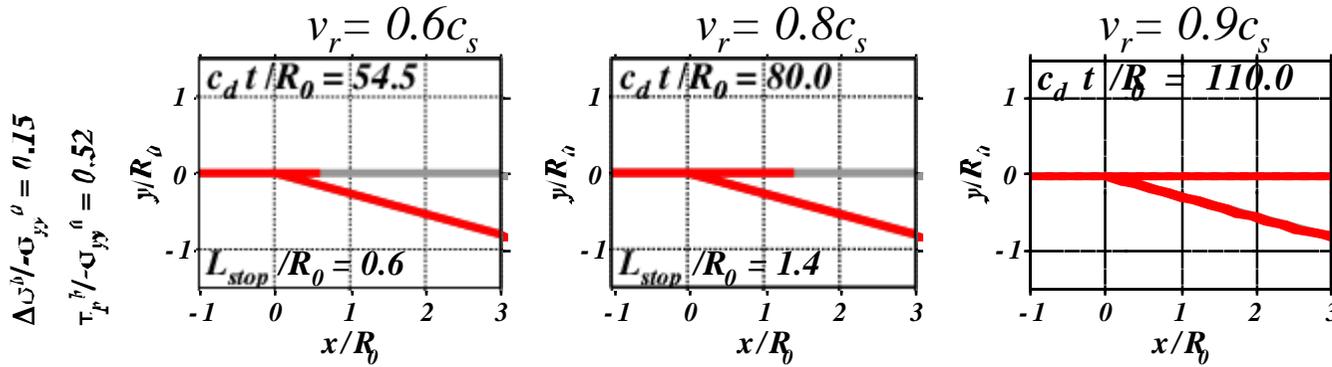
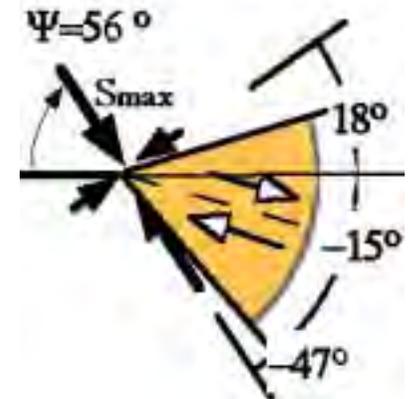
$$\Delta\sigma^b / -\sigma_{yy}^0 = 0.03$$

$$\tau_{xy}^b / -\sigma_{yy}^0 = 0.48$$

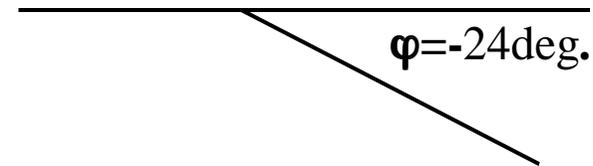


San Fernando 1971 (Thrust Type)

High inclination
(Case $-\sigma_{xx}^0 / -\sigma_{yy}^0 = 0.8$)

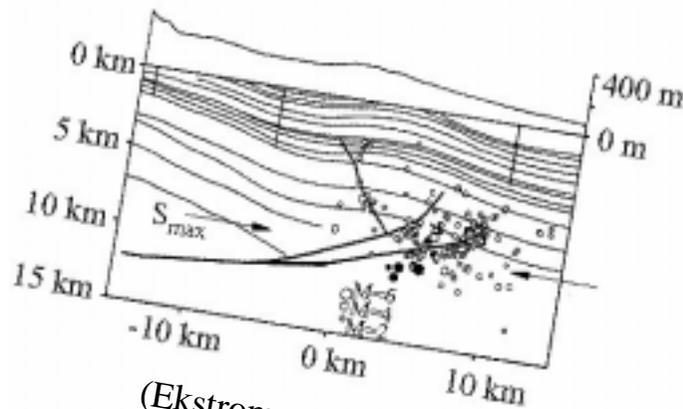
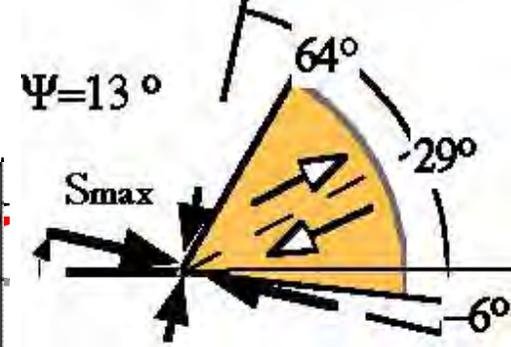
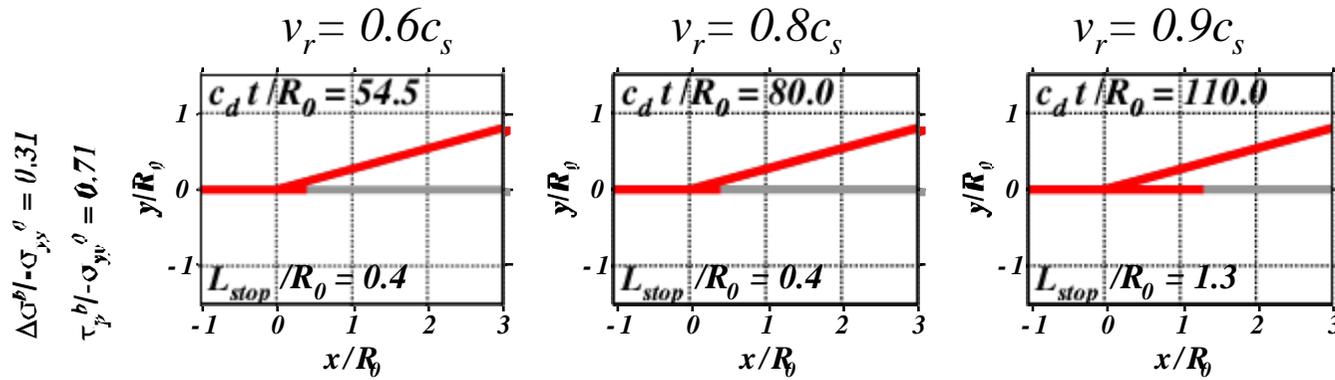


S_{max}
 $\Psi = 53 \text{deg.}$



(Horizontal S_{max} assumed)

Kettleman Hills 1985 (Thrust Type)



(Ekstrom et al., 1992)

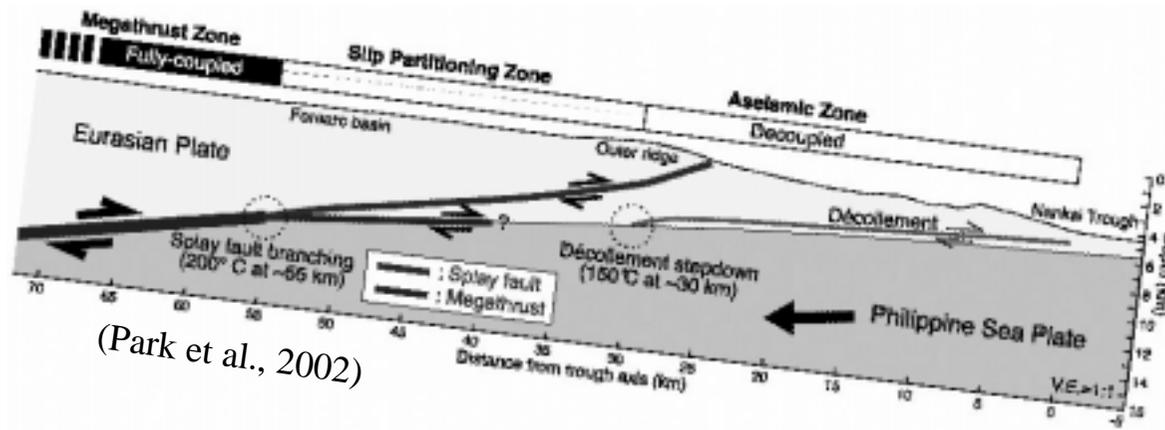
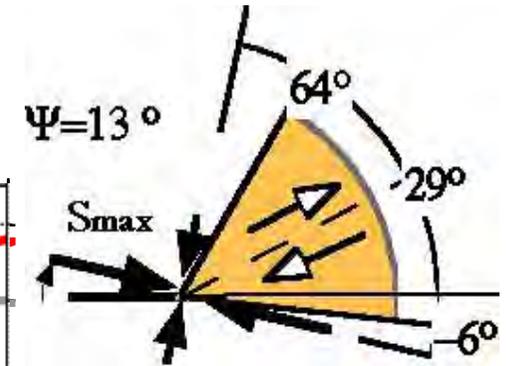
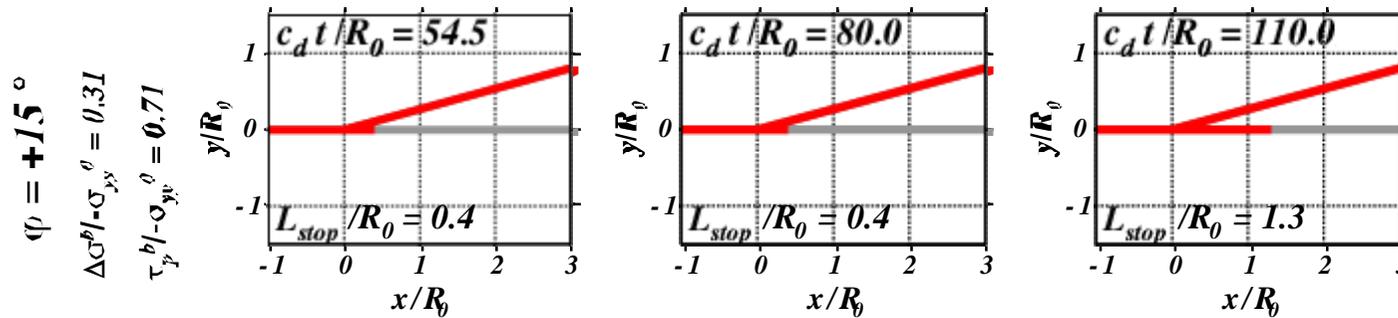
S_{max}
 $\Psi = 12-14deg.$

$\phi = 15deg.$

(Horizontal S_{max} assumed)

動的に分岐したかは不明

Nankai Subduction Zone (Thrust Type)



(Park et al., 2002)

S_{max}
 $\Psi = 7-8\text{deg.}$

$\varphi = 3-10\text{deg.}$

(Horizontal S_{max} assumed)

動的に分岐したかは不明

まとめ

- 動的モデルによる分岐断層上の破壊伝播シミュレーションを行った。
- **最大主軸の角度**が主断層面に対して傾くにつれ、破壊に適する分岐断層の方向は引張側から圧縮側へ移る。
- 主・分岐の**両断層上の同時破壊**は、分岐角度が小さいと困難。
- しかし、**破壊速度が増す**と波動応力の効果で同時破壊が起きる。
- また、**分岐角度が大きい**と同時破壊が可能になる。
- 自然地震の主軸の方向と選択破壊面の方向は本研究と調和的である。