Advanced geomechanics - WP2

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Exercise 1

Suport functions:

In [1]:
```python
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import matplotlib as mpl

plt.style.use('default')   ## reset!
plt.style.use('paper.mplstyle')

def shear( sig_n, s1, s2 ) :
    """
    Creates a shear series for given values of principal stresses and sig_n
    """
    center = (s1 + s2)/2
    radius = (s1 - s2)/2
    dx = sig_n - center
    tau_sq = radius * radius - dx * dx
    tau_sq[ tau_sq < 0 ] = None
    return np.sqrt( tau_sq )

def mohr(s1, s2, s3, ax, title="") :
    """
    Plot Mohr diagram
    """
    # Setup data
    npts = 1000

    [s1,s2,s3] = sorted([s1,s2,s3], reverse=True)
    step = (s1-s3)/npts
    sig_n = np.sort( np.append( np.arange(s3,s1,step), [s1, s2, s3]) )

    s12_tau = shear( sig_n, s1, s2 )
    s13_tau = shear( sig_n, s1, s3 )
    s23_tau = shear( sig_n, s2, s3 )

    # Do the plotting stuff
    ax.plot(sig_n, s12_tau, c='gray')
    ax.plot(sig_n, s23_tau, c='gray')
    ax.plot(sig_n, s13_tau, c='gray')

    ax.fill_between(sig_n, s12_tau, s13_tau, color='lightgray')
    ax.fill_between(sig_n, s23_tau, s13_tau, color='lightgray' )

    min, max = 900, 3500
    ax.set_xlim(min, max)
    ax.set_ylim(0, max-min)
    ax.set_title(title, fontsize=20)
    ax.set_ylabel("Shear stress ($\\tau$)")
    ax.set_xlabel("Effective normal stress ($\sigma_n$)")

    return ax

def mohr_to_axis(Sig, ax) :
    npts = 1000

    s1 = Sig[0,0]
    s2 = Sig[1,1]
    s3 = Sig[2,2]
    [s1,s2,s3] = sorted([s1,s2,s3], reverse=True)
    step = (s1-s3)/npts
    sig_n = np.sort( np.append( np.arange(s3,s1,step), [s1, s2, s3]) )

    s12_tau = shear( sig_n, s1, s2 )
    s13_tau = shear( sig_n, s1, s3 )
    s23_tau = shear( sig_n, s2, s3 )

    # Do the plotting stuff
    ax.plot(sig_n, s12_tau, c='gray')
    ax.plot(sig_n, s23_tau, c='gray')
    ax.plot(sig_n, s13_tau, c='gray')

    ax.fill_between(sig_n, s12_tau, s13_tau, color='lightgray')
    ax.fill_between(sig_n, s23_tau, s13_tau, color='lightgray' )


def print_matrix(A,title, ax=None) :
    txt = f"${title} = " +\
          r"\begin{bmatrix}" +\
          r' \\ '.join(r' & '.join('%0.0f' % (x+1e-6) for x in y) for y in A) +\
          r'\end{bmatrix}$'
    if not ax :
        fig,ax = plt.subplots()
    fig = ax.figure
    fig.set_size_inches(3, 1)
    ax.xaxis.set_visible(False)
    ax.yaxis.set_visible(False)
    with mpl.rc_context({'text.usetex':1, 'text.latex.preamble': r'\usepackage{amsmath}'}):
      ax.text( 0.1, 0.5, txt, fontsize=8 )
      fig.tight_layout()
      plt.show()

def SG_to_fault( Sg, Pp, dip, strike ) :
    # Fault coordinate system
    SS = np.sin(strike)
    CS = np.cos(strike)
    SD = np.sin(dip)
    CD =np.cos(dip)

    Nn = np.array([ -SS*SD, CS*SD, -CD ])
    Ns = np.array([ CS, SS, 0 ])
    Nd = np.array([ -SS*CD, CS*CD, SD ])

    SSg = Sg
    # Project Sg to the fault coordinate system
    T = SSg @ Nn
    sn = np.dot(T , Nn) - Pp
    tau = np.sqrt( np.dot(T , Nd)**2 + np.dot(T , Ns)**2 )

    return sn, tau

def process_fracture_set( Sg, Pp, DIP, STRIKE ) :
    SIGn, TAU = np.array([]), np.array([])
    for d,s in zip(DIP,STRIKE) :
        sn, tau = SG_to_fault( Sg, Pp, d, s )
        SIGn = np.append( SIGn, sn)
        TAU  = np.append( TAU, tau )
    return SIGn, TAU

import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
plt.style.use('default')   ## reset!
plt.style.use('paper.mplstyle')

def SP_to_SG(Sp, alpha, beta, gamma) :
  # ROTATION MATRIX
  CA, SA = np.cos(alpha), np.sin(alpha)
  CB, SB = np.cos(beta),  np.sin(beta)
  CG, SG = np.cos(gamma), np.sin(gamma)
  RPG = np.array(
        [ [ CA*CB,               SA*CB             ,   -SB  ],
          [ CA*SB*SG - SA*CG,    SA*SB*SG + CA*CG , CB*SG  ],
          [ CA*SB*CG + SA*SG,    SA*SB*CG - CA*SG , CB*CG  ]]
  )

  # MATRIX MULTIPLICATION - STRESS IN GEOGRAPHIC COORDINATES
  Sg = RPG.T @ Sp @ RPG
  return Sg
```

1 - Input the principal stress tensor at Depth E in the principal directions coordinate system and calculate the tensor in the geographical coordinate system.

In [2]:
```python
# POINT E TOTAL STRESS
Sp = np.array(
     [ [11322, 0     ,    0 ],
       [ 0   , 9540  ,    0 ],
       [ 0   , 0     , 9249 ] ]
);
# Pore pressure
Pp = 7988

Sg = SP_to_SG ( Sp, np.pi/2, 0, np.pi/2 )

Sigma_g = Sg.copy()
Sigma_g[0,0] = Sigma_g[0,0] - Pp
Sigma_g[1,1] = Sigma_g[1,1] - Pp
Sigma_g[2,2] = Sigma_g[2,2] - Pp

## OUTPUT
print_matrix(Sp, "S_P")
print_matrix(Sg, "S_G")
print_matrix(Sigma_g, "Sigma_G")
# print(f"Sp = \n{Sp}")
# print(f"\nSg = \n{Sg}")
# print(f"\nSigma_g = \n{Sigma_g}")
```

$$S_P = \begin{bmatrix} 11322 & 0 & 0 \\ 0 & 9540 & 0 \\ 0 & 0 & 9249 \end{bmatrix}$$

$$S_G = \begin{bmatrix} 9249 & 0 & 0 \\ 0 & 11322 & 0 \\ 0 & 0 & 9540 \end{bmatrix}$$

$$Sigma_G = \begin{bmatrix} 1261 & 0 & 0 \\ 0 & 3334 & 0 \\ 0 & 0 & 1552 \end{bmatrix}$$

2 - Generate 100 randomly distributed fracture orientations (strike and dip) and compute their effective normal stress and shear stress. Plot all in a σ_n versus τ diagram together with the 3D Mohr circle(s). EXTRA 1 (not required): color symbols for each point (σ_n, τ) from blue to red (e.g., JET colormap) according to the value of τ/σ_n. EXTRA 2 (not required): plot all fractures in a stereonet projection with symbols colored by the value of τ/σ_n.

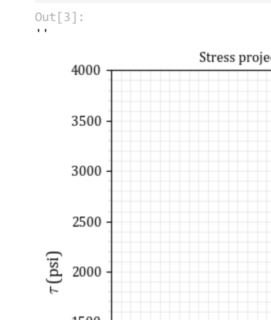
3 - Are there any fractures prone to shear slip (assume friction coefficient $\mu = 0.5 \pm 0.1$)? What fractures are likely to be hydraulically conductive based on the τ/σ_n criterion and which others are not?

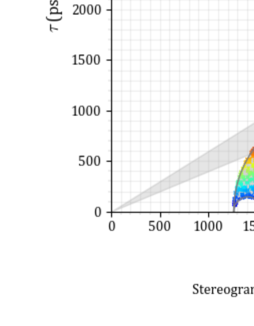
Answer: Yes. They are the ones inside the shaded area of the plots.

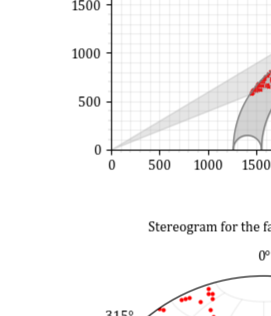
Note: *I used 1000 fractures, as the results looked nicer to analyze*

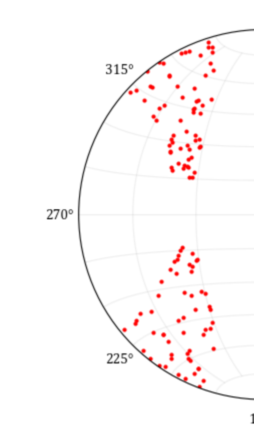
In [3]:
```python
import numpy as np
import mplstereonet
import matplotlib.pyplot as plt

N=1000
DIP    = np.random.rand(N) * np.pi/2
STRIKE = np.random.rand(N) * np.pi * 2

# Processing
SIGn, TAU = process_fracture_set(Sg, Pp, DIP, STRIKE)

# Shear limits
shear_x = np.linspace(0,4000,10)
shear_y_p = shear_x * 0.6
shear_y_n = shear_x * 0.4

# Plot TAU x SIGn
fig, ax = plt.subplots()
fig.set_size_inches(5,5)
mohr_to_axis( Sigma_g, ax )
ax.scatter(SIGn , TAU, s=5, marker = 'x', c=TAU/SIGn, cmap='jet')
ax.fill_between(shear_x, shear_y_n, shear_y_p, color='gray', alpha=0.2)
# Labels, limits
ax.set_xlabel("$\sigma_n$ (psi)")
ax.set_ylabel("$\\tau$ (psi)")
ax.set_xlim(0,4000)
ax.set_ylim(0,4000)
ax.set_title("Stress projection on the fault planes")
fig.tight_layout()

# Plot full stereonet
fig, ax = mplstereonet.subplots()
x,y = STRIKE*180/np.pi, DIP*180/np.pi
lons, lats = mplstereonet.pole(x,y)
ax.scatter(lons, lats, c=TAU/SIGn, s=10, cmap='jet')
ax.set_title('Stereogram for all faults', y=1.10)

# Filter only the faults close to shear
stmap = ( TAU/SIGn > 0.4 )
x = SIGn[stmap]
y = TAU[stmap]

# Plot filtered TAU x SIGn
fig, ax = plt.subplots()
fig.set_size_inches(5,5)
mohr_to_axis( Sigma_g, ax )
ax.scatter(x, y, s=5, marker = 'x', c='r')
ax.fill_between(shear_x, shear_y_n, shear_y_p, color='gray', alpha=0.2)
ax.set_xlabel("$\sigma_n$ (psi)")
ax.set_ylabel("$\\tau$ (psi)")
ax.set_xlim(0,4000)
ax.set_ylim(0,4000)
ax.set_title("Stress projection on the fault planes for the faults close to shear")

# Plot filtered stereonet
x = (STRIKE*180/np.pi)[stmap]
y = (DIP*180/np.pi)[stmap]
fig, ax = mplstereonet.subplots()
ax.pole(x,y,markersize=2,color='r')
ax.set_title('Stereogram for the faults close to shear', y=1.10)

''
```

Out[3]:
''









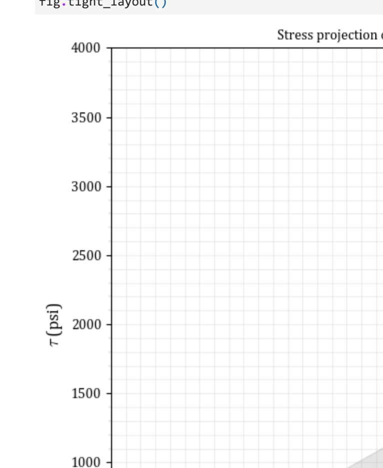
4 - Wellbore images actually show that there are two major fracture sets:

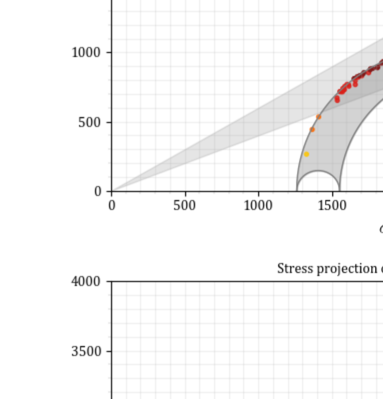
- Set 1: strike = 60 +/- 10 degrees, dip = 80 +/- 5 degrees
- Set 2: strike = 10 +/- 10 degresn, dip = 60 +/- 5 degrees

Plot results for 20 fractures for each set (errors represent one standard deviation of a normal distribution). Which fracture set is more likely to slip in shear? Why?

Answer: Set 2 is more likely to slip in shear, because their stress state are more likely to touch the TAU/SIGn limit considered.

In [4]:
```python
import numpy as np

N=50
s1_stk = np.random.normal(60,10,N) * np.pi / 180
s1_dip = np.random.normal(80,5,N)  * np.pi / 180

s2_stk = np.random.normal(10,10,N) * np.pi / 180
s2_dip = np.random.normal(60,5,N)  * np.pi / 180

s1_sn, s1_tau = process_fracture_set( Sg, Pp, s1_dip, s1_stk )
s2_sn, s2_tau = process_fracture_set( Sg, Pp, s2_dip, s2_stk )

import matplotlib as mpl
n_colors = 11
jetcm = mpl.colormaps['jet'].resampled(n_colors) # [0,1]
bins = np.linspace(-.5,0.6,n_colors)

s1_colors = [jetcm(i) for i in np.digitize(s1_tau / s1_sn, bins )]
s2_colors = [jetcm(i) for i in np.digitize(s2_tau / s2_sn, bins )]

# Plot TAU x SIGn
fig, ax = plt.subplots()
fig.set_size_inches(7,6.5)
mohr(1552,3334,1261, ax, "Point E")

ax.scatter(s1_sn , s1_tau, s=8, marker = 'o', c=s1_colors, alpha=.8)
ax.fill_between(shear_x, shear_y_n, shear_y_p, color='gray', alpha=0.2)
# Labels, limits
ax.set_xlabel("$\sigma_n$ (psi)")
ax.set_ylabel("$\\tau$ (psi)")
ax.set_xlim(0,4000)
ax.set_ylim(0,4000)
ax.set_title("Stress projection on the fault planes - SET 1")
fig.tight_layout()

# Plot TAU x SIGn
fig, ax = plt.subplots()
fig.set_size_inches(7,6.5)

mohr(1552,3334,1261, ax, "Point E")
ax.scatter(s2_sn , s2_tau, s=8, marker = 'o', c=s2_colors, alpha=.8)
ax.fill_between(shear_x, shear_y_n, shear_y_p, color='gray', alpha=0.2)
# Labels, limits
ax.set_xlabel("$\sigma_n$ (psi)")
ax.set_ylabel("$\\tau$ (psi)")
ax.set_xlim(0,4000)
ax.set_ylim(0,4000)
ax.set_title("Stress projection on the fault planes - SET 2")
fig.tight_layout()
```





Exercise 2

Prepare the database.

In [5]:
```python
import pandas as pd
import numpy as np

df = pd.read_csv("fault_data.txt", sep='\t')

dSv_dz = 1 # psi/ft
dPp_dz = 0.44 # psi/ft

df.origin = df.origin.apply(eval).apply(np.array)
df.end = df.end.apply(eval).apply(np.array)

df['dist'] = df.end - df.origin
df['strike'] = df.apply( lambda x: np.arctan2(x.dist[0], x.dist[1]) , axis=1)
df['dip'] = df.dip * np.pi / 180
mask = df.dip_dir.str.contains('N')
df.loc[mask,"strike"] = df[mask].strike + np.pi

df['strike_deg'] = df.strike * 180 / np.pi
df['dip_deg'] = df.dip * 180 / np.pi

df['Sv'] = dSv_dz * df.depth
df['Pp'] = dPp_dz * df.depth
df['Shmin'] = 0.76 * df.Sv
df['Shmax'] = 0.79 * df.Sv
df['Sg'] = df.apply( lambda x : np.array( [ [ x.Shmin, 0, 0 ], [ 0, x.Shmax, 0 ], [ 0, 0, x.Sv ]] ), axis=1 )
df['Sigg'] = df.apply( lambda x : np.array( [ [ (x.Shmin-x.Pp), 0, 0 ], [ 0, (x.Shmax-x.Pp), 0 ], [ 0, 0, (x.Sv-x.Pp) ]
df['Sigg_div_Sigv'] = df.apply( lambda x : np.array( [ [ (x.Shmin-x.Pp)/(x.Sv-x.Pp), 0, 0 ], [ 0, (x.Shmax-x.Pp)/(x.Sv-
df['Sigv'] = df.Sv - df.Pp

def process_fracture_set_2( SG, PP, DIP, STRIKE ) :
    SIGn, TAU = np.array([]), np.array([])
    for Sg, Pp, d,s in zip(SG, PP, DIP,STRIKE) :
        sn, tau = SG_to_fault( Sg, Pp, d, s )
        SIGn = np.append( SIGn, sn)
        TAU  = np.append( TAU, tau )
    return SIGn, TAU

SIGn, TAU = process_fracture_set_2( df.Sg, df.Pp, df.dip, df.strike )

df['SIGn'] = SIGn
df['TAU'] = TAU

df['SIGn_div_Sv'] = df.SIGn / df.Sigv
df['TAU_div_Sv'] = df.TAU / df.Sigv

# Dump some columns of the database
df[["id","dip_deg","strike_deg","dip_dir","Sv", "Shmin", "Shmax", "Pp"]]
```

Out[5]:

	id	dip_deg	strike_deg	dip_dir	Sv	Shmin	Shmax	Pp
0	F1a	53.0	102.396596	SW	7250	5510.0	5727.5	3190.0
1	F1b	53.0	84.619659	S	7150	5434.0	5648.5	3146.0
2	F1c	53.0	76.685609	SE	7050	5358.0	5569.5	3102.0
3	F1d	53.0	52.908764	SE	7300	5548.0	5767.0	3212.0
4	F2	52.0	60.958149	SE	7500	5700.0	5925.0	3300.0
5	F3	55.0	50.748072	SE	7800	5928.0	6162.0	3432.0
6	F4a	56.0	74.536837	SE	7400	5624.0	5846.0	3256.0
7	F4b	56.0	91.718757	S	7400	5624.0	5846.0	3256.0
8	F4c	56.0	121.572028	SW	7500	5700.0	5925.0	3300.0
9	F4d	56.0	95.453238	S	7700	5852.0	6083.0	3388.0
10	F4e	56.0	116.032504	SW	8300	6308.0	6557.0	3652.0
11	F4f	56.0	116.913623	SW	8350	6346.0	6596.5	3674.0
12	F5a	56.0	137.490598	SW	8000	6080.0	6320.0	3520.0
13	F5b	56.0	151.695283	SW	8200	6232.0	6478.0	3608.0
14	F6a	30.0	94.776331	SW	8000	6080.0	6320.0	3520.0
15	F6b	30.0	89.400485	S	8100	6156.0	6399.0	3564.0
16	F6c	30.0	76.824619	SE	8150	6194.0	6438.5	3586.0
17	F7a	50.0	124.045386	SW	8200	6232.0	6478.0	3608.0
18	F7b	50.0	143.914109	SW	8150	6194.0	6438.5	3586.0
19	F7c	50.0	119.686441	SW	8200	6232.0	6478.0	3608.0
20	F8a	56.0	56.230594	SE	8500	6460.0	6715.0	3740.0
21	F8b	56.0	44.908473	SE	8400	6384.0	6636.0	3696.0
22	F8c	56.0	86.865229	S	8400	6384.0	6636.0	3696.0
23	F9	37.0	194.150975	NW	8450	6422.0	6675.5	3718.0

1 - Calculate the stress tensor for each fault. The direction of S_{hmin} is N-S.

In [6]:
```python
df.apply( lambda x: print(f"\n{x.id}=\n{x.Sg}") , axis=1)
''
```

```
F1a=
[[5510.     0.     0. ]
 [   0.  5727.5    0. ]
 [   0.     0.  7250. ]]

F1b=
[[5434.     0.     0. ]
 [   0.  5648.5    0. ]
 [   0.     0.  7150. ]]

F1c=
[[5358.     0.     0. ]
 [   0.  5569.5    0. ]
 [   0.     0.  7050. ]]

F1d=
[[5548.    0.    0.]
 [   0. 5767.    0.]
 [   0.    0. 7300.]]

F2=
[[5700.    0.    0.]
 [   0. 5925.    0.]
 [   0.    0. 7500.]]

F3=
[[5928.    0.    0.]
 [   0. 6162.    0.]
 [   0.    0. 7800.]]

F4a=
[[5624.    0.    0.]
 [   0. 5846.    0.]
 [   0.    0. 7400.]]

F4b=
[[5624.    0.    0.]
 [   0. 5846.    0.]
 [   0.    0. 7400.]]

F4c=
[[5700.    0.    0.]
 [   0. 5925.    0.]
 [   0.    0. 7500.]]

F4d=
[[5852.    0.    0.]
 [   0. 6083.    0.]
 [   0.    0. 7700.]]

F4e=
[[6308.    0.    0.]
 [   0. 6557.    0.]
 [   0.    0. 8300.]]

F4f=
[[6346.     0.     0. ]
 [   0.  6596.5    0. ]
 [   0.     0.  8350. ]]

F5a=
[[6080.    0.    0.]
 [   0. 6320.    0.]
 [   0.    0. 8000.]]

F5b=
[[6232.    0.    0.]
 [   0. 6478.    0.]
 [   0.    0. 8200.]]

F6a=
[[6080.    0.    0.]
 [   0. 6320.    0.]
 [   0.    0. 8000.]]

F6b=
[[6156.    0.    0.]
 [   0. 6399.    0.]
 [   0.    0. 8100.]]

F6c=
[[6194.     0.     0. ]
 [   0.  6438.5    0. ]
 [   0.     0.  8150. ]]

F7a=
[[6232.    0.    0.]
 [   0. 6478.    0.]
 [   0.    0. 8200.]]

F7b=
[[6194.     0.     0. ]
 [   0.  6438.5    0. ]
 [   0.     0.  8150. ]]

F7c=
[[6232.    0.    0.]
 [   0. 6478.    0.]
 [   0.    0. 8200.]]

F8a=
[[6460.    0.    0.]
 [   0. 6715.    0.]
 [   0.    0. 8500.]]

F8b=
[[6384.    0.    0.]
 [   0. 6636.    0.]
 [   0.    0. 8400.]]

F8c=
[[6384.    0.    0.]
 [   0. 6636.    0.]
 [   0.    0. 8400.]]

F9=
[[6422.     0.     0. ]
 [   0.  6675.5    0. ]
 [   0.     0.  8450. ]]
```

Out[6]:
''

2 - Calculate the effective normal stress σ_n and shear stress τ on each fault and plot the results together in a normalized 3D Mohr circle with x-axis (σ_n/σ_v) and y-axis (τ/σ_v). Assume hydrostatic pore pressure $\mathrm{d}P_p/\,\mathrm{d}z = 0.44$ psi/ft.

3 - Are there any faults prone to reactivation (assume friction coefficient $\mu = 0.6$)? If yes, what faults are those?

Answer: No. There are no faults prone to reactivation.

---

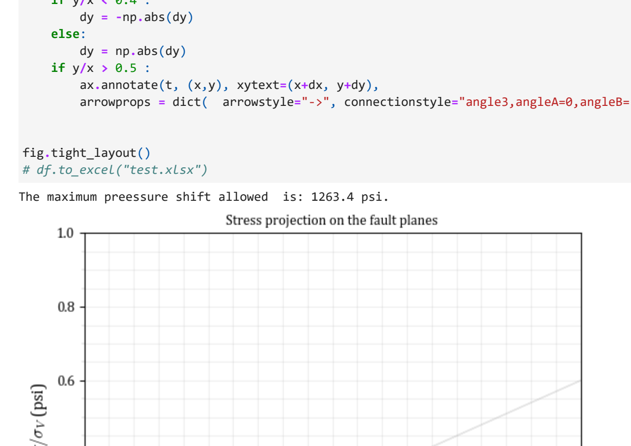
4 - Assuming that fluid injection would shift Mohr circles to lower σ_n values without change of τ values (circle moves to the left without change of diameter - conservative assumption), what is the maximum allowable pressure increase without causing fault reactivation?

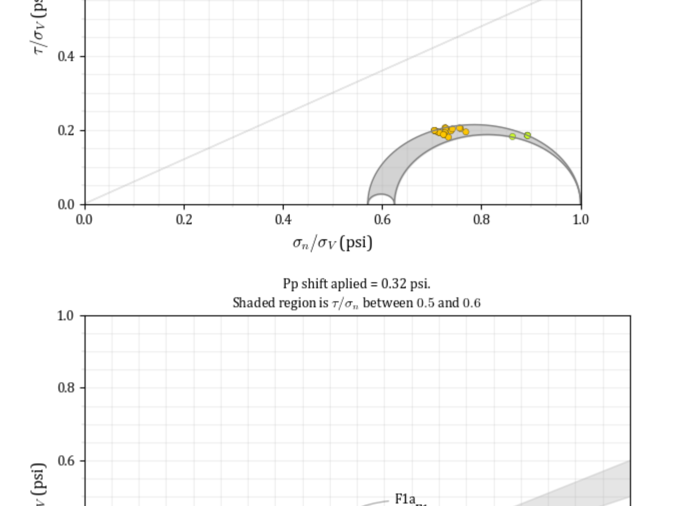
Answer: I could find a pressure shift of around 1263 psi before any shear would occur. I used $0.5 < \mu < 0.6$ as the range of analysis

In [10]:

```python
import matplotlib as mpl

SIGn, TAU = process_fracture_set_2( df.Sg, df.Pp, df.dip, df.strike )

# Set values on the dataframe
df['SIGn'] = SIGn
df['TAU'] = TAU
df['SIGn_div_Sv'] = df.SIGn / df.Sigv
df['TAU_div_Sv'] = df.TAU / df.Sigv

df['TAU_div_SIGn'] = df.TAU_div_Sv / df.SIGn_div_Sv

# Plot TAU x SIGn
fig, ax = plt.subplots()

n_colors = 11
jetcm = mpl.colormaps['jet'].resampled(n_colors) # [0,1]
bins = np.linspace(-.5,0.7,n_colors)
c = [jetcm(i) for i in np.digitize(df.TAU_div_Sv / df.SIGn_div_Sv, bins )]

for k, x in df.iterrows() :
    mohr_to_axis( x.Sigg_div_Sigv, ax )
    break

# Shear limits
shear_x = np.linspace(0,6000,10)
shear_y_p = shear_x * 0.6
shear_y_n = shear_x * 0.6
ax.fill_between(shear_x, shear_y_n, shear_y_p, color='gray', alpha=0.2)
# Labels, limits
ax.set_xlabel("$\sigma_n / \sigma_V$ (psi)")
ax.set_ylabel("$\\tau / \sigma_V$ (psi)")
ax.set_xlim(0,1)
ax.set_ylim(0,1)
ax.set_title("Stress projection on the fault planes")
ax.scatter(df.SIGn_div_Sv , df.TAU_div_Sv, s=20, marker = 'o', c=c, edgecolors='k', linewidth=.2)


#
# Maximum injection pressure
#

# Plot TAU x SIGn
fig, ax = plt.subplots()

for k, x in df.iterrows() :
    mohr_to_axis( x.Sigg_div_Sigv, ax )
    break

ax.scatter(df.SIGn_div_Sv , df.TAU_div_Sv, s=20, marker = 'x', c='k')
Pp_shift = 0.32
df["max_Pp"] = df.Sigv * Pp_shift
print(f"The maximum preessure shift allowed  is: {df.max_Pp.min():.1f} psi.")
c = [jetcm(i) for i in np.digitize(df.TAU_div_Sv / (df.SIGn_div_Sv-Pp_shift), bins )]

for k, x in df.iterrows() :
    S_shift = x.Sigg_div_Sigv.copy()
    S_shift[0,0] = S_shift[0,0] - Pp_shift
    S_shift[1,1] = S_shift[1,1] - Pp_shift
    S_shift[2,2] = S_shift[2,2] - Pp_shift
    mohr_to_axis( S_shift, ax )
    break

ax.scatter(df.SIGn_div_Sv - Pp_shift, df.TAU_div_Sv, s=20, marker = 'o', c=c, edgecolors='k', linewidth=.2)
# Shear limits
shear_x = np.linspace(0,6000,10)
shear_y_p = shear_x * 0.5
shear_y_n = shear_x * 0.6
ax.fill_between(shear_x, shear_y_n, shear_y_p, color='gray', alpha=0.2)
# Labels, limits
ax.set_xlabel("$\sigma_n / \sigma_V$ (psi)")
ax.set_ylabel("$\\tau / \sigma_V$ (psi)")
ax.set_xlim(0,1)
ax.set_ylim(0,1)
ax.set_title(f"Pp shift aplied = {Pp_shift} psi.\nShaded region is $\\tau/\sigma_n$ between $0.5$ and $0.6$")

df["Tau_div_Sign_Shifted"] = df.TAU_div_Sv / (df.SIGn_div_Sv - Pp_shift)

for t,x,y in zip(df.id, df.SIGn_div_Sv - Pp_shift, df.TAU_div_Sv) :
    dx = np.random.rand()*.4 - .2
    dy = np.random.rand()*.3
    if y/x < 0.4 :
        dy = -np.abs(dy)
    else:
        dy = np.abs(dy)
    if y/x > 0.5 :
        ax.annotate(t, (x,y), xytext=(x+dx, y+dy),
        arrowprops = dict(  arrowstyle="->", connectionstyle="angle3,angleA=0,angleB=-90", alpha=0.3))


fig.tight_layout()
# df.to_excel("test.xlsx")
```

The maximum preessure shift allowed is: 1263.4 psi.





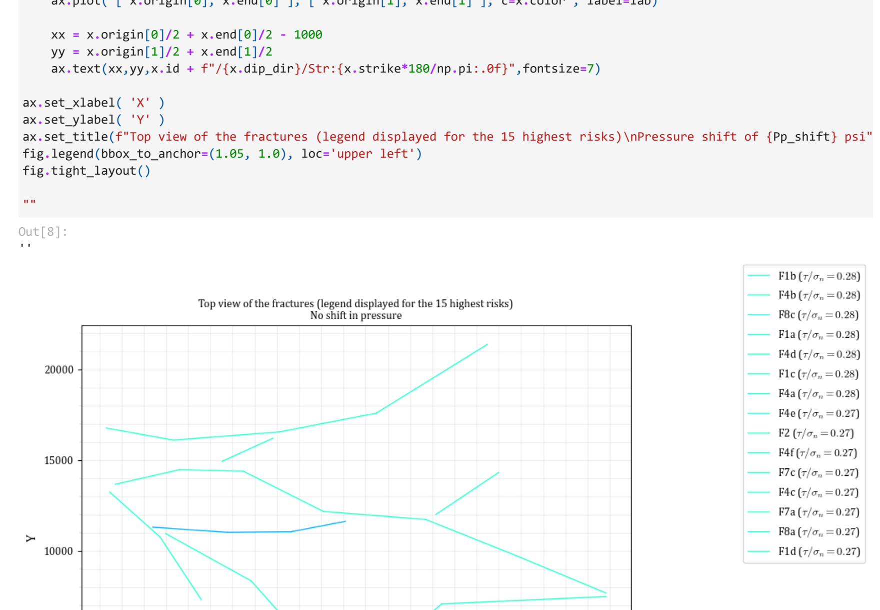
5 - Plot the faults as straight lines in a 2D top view map and identify faults closer to reactivation. Suggestion: color segments according to the value of τ/σ_n where red is high likelihood for reactivation and blue is low likelihood for reactivation.

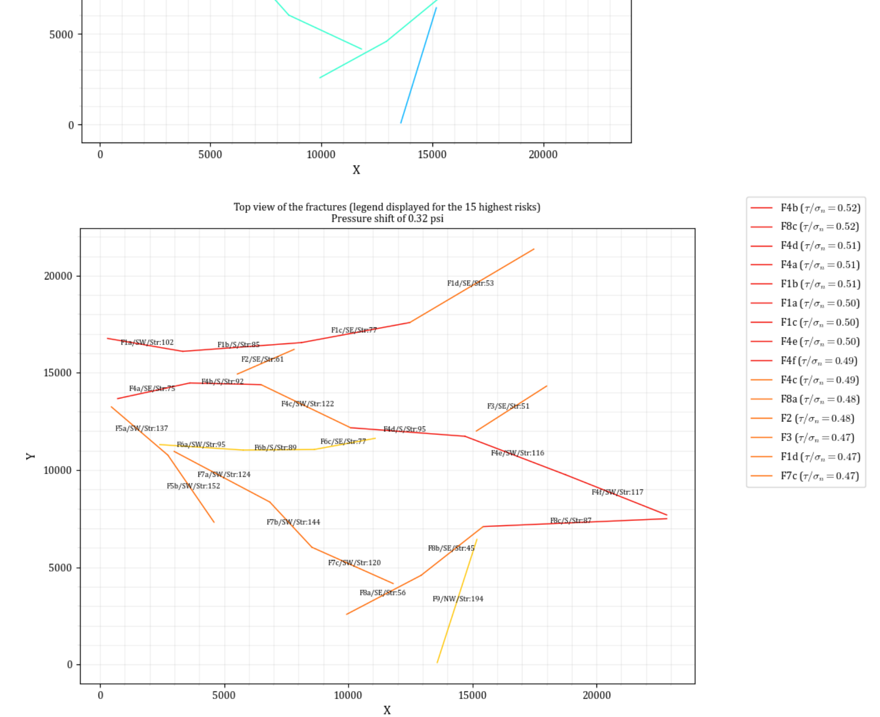
In [8]:

```python
import matplotlib as mpl
import matplotlib.pyplot as plt
n_colors = 11
jetcm = mpl.colormaps['jet'].resampled(n_colors) # [0,1]

df['color_bin'] = pd.cut( df.TAU_div_SIGn, bins=np.linspace(0,0.6,n_colors), labels=False )
df['color'] = df.apply( lambda x : jetcm( x.color_bin ), axis=1)

df_sorted = df.sort_values("TAU_div_SIGn",ascending=False)
fig, ax = plt.subplots()
fig.set_size_inches(9,7)
count=0
for k, x in df_sorted.iterrows() :
    lab = x.id + f" ($\\tau/\sigma_n={x.TAU_div_SIGn:.2f}$)"
    count = count + 1
    if count > 15 : lab = ""
    ax.plot( [ x.origin[0], x.end[0] ], [ x.origin[1], x.end[1] ], c=x.color , label=lab)

ax.set_xlabel( 'X' )
ax.set_ylabel( 'Y' )
ax.set_title("Top view of the fractures (legend displayed for the 15 highest risks)\nNo shift in pressure")
fig.legend(bbox_to_anchor=(1.05, 1.0), loc='upper left')


#
# Now shifting the pressure
#
bins = np.linspace(-.5,0.6,n_colors)
df['color_bin'] = pd.cut( df.Tau_div_Sign_Shifted, bins=bins, labels=False )
df['color'] = df.apply( lambda x : jetcm( x.color_bin ), axis=1)

df_sorted = df.sort_values("Tau_div_Sign_Shifted",ascending=False)
fig, ax = plt.subplots()
fig.set_size_inches(9,7)

count=0
for k, x in df_sorted.iterrows() :
    lab = x.id + f" ($\\tau/\sigma_n={x.Tau_div_Sign_Shifted:.2f}$)"
    count = count + 1
    if count > 15 : lab = ""
    ax.plot( [ x.origin[0], x.end[0] ], [ x.origin[1], x.end[1] ], c=x.color , label=lab)

    xx = x.origin[0]/2 + x.end[0]/2 - 1000
    yy = x.origin[1]/2 + x.end[1]/2
    ax.text(xx,yy,x.id + f"/{x.dip_dir}/Str:{x.strike*180/np.pi:.0f}",fontsize=7)

ax.set_xlabel( 'X' )
ax.set_ylabel( 'Y' )
ax.set_title(f"Top view of the fractures (legend displayed for the 15 highest risks)\nPressure shift of {Pp_shift} psi")
fig.legend(bbox_to_anchor=(1.05, 1.0), loc='upper left')
fig.tight_layout()

""
```

Out[8]:

''





In [ ]: