Seismic Focal Mechanisms in R

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Abstract

Plot focal Mechanisms and stereonets for seismic data.

1 Example

Start out by calling the RFOC library,

```
> library(RFOC)
> data(PKAM)
> numk = length(PKAM$LATS)
> payr = paste(collapse = "-", range(PKAM$yr))
```

2 Focal Mechanisms and seismic radiation

One meta-data parameter stored on seismic data is the polarity of the first motion. The polarity is recorded from the waveform display, and it indicates whether the motion on the vertical component was up or down during the first arrival of the waves. Polarity data are stored and used to derive the earthquake *focal mechanism*, which describes the orientation and slip of the fault that produced the earthquake at he hypocenter. Inversion programs are used to determine the best fitting focal mechanism, which are then displayed graphically to visualize sense of rupture in the subsurface. The inversions are usually derived via grid search and there are several established codes available for this purpose. Here we will not be concerned with programs that invert the polarity but rather with the graphical display and manipulations of the results. The R codes presented here are not limited to analysis of focal mechanisms, but can be applied to numerous other spherically distributed data that often arise in Geological applications.

3 Stereo-net representation of fault mechanics

Stereo-nets, planar projections of spherical data, are common in geology and geophysical applications. For earthquake analysis, fault studies, crystallography, material fabric analysis and numerous other spherically distributed data, equal-area (Schmidt) and equal-angle (Wulff) are the most common projections, with occasional polar representations employed. In geological applications, representations of fault planes are displayed as great circles or poles on the stereonet. Motions of continents in plate tectonics are represented as poles and great circles. In seismology, stereo-nets are used to describe earthquake double couple focal mechanisms and particle motion at a single station in three-dimensions. All of these involve either global or local projection of data on a sphere. The programs presented here in RFOC are general and may be used for any kind of spherically distributed information. The specific application of focal mechanisms, however, requires calculation and display of information derived from the strike, dip and rake of an earthquake. The slip vectors correspond possibly to striations one might observe on the fault surface as the earth scrapes the two planes during rupture.

When earthquakes occur below the surface they radiate energy along two sets of orthogonal directions forming two sets of force couples called a double couple. (Landslides can radiate single couple patterns and explosions have an isotropic component.) The double couple solutions can be derived from the first motions recorded at seismographic stations distributed at the surface by projecting the ray-paths of the waves back to the hypocenter and plotting the directions of the first motions on a stereographic projection of the focal sphere. The resulting solution is a set of two planes, one representing the actual fault plane where the earth ruptured, the other is called the auxiliary plane that also radiates energy towards the surface. The data consists of points on the focal sphere indicating whether the motion was away or towards the earthquake hypocenter. These are plotted and a set of best fitting orthogonal planes are determined, usually by grid search methods. A cross sectional view of how a geophysicist views the an example double couple solution is shown in Figure 1 where are a normal fault is shown from the side and in mapview showing the beachball representation. A second example showing relavent quantitative measures derived from the focal solution are shown in Figure 2.

A set of poles (points on the sphere) can be extracted from the focal mechanism that relate geophysical information about the nature of the earthquake orientation and slip vector and the compressional and tensional radiation axes. In RFOC one can extract the relevant information easily with a call to a conversion program and plotting,

```
> mc = CONVERTSDR(65, 32, -34)
> printMEC(mc)
```

```
Plane 1: [1]  155   32
Plane 2: [1]  274.77   72.76
Vector 1: [1]  94.77  17.24
```

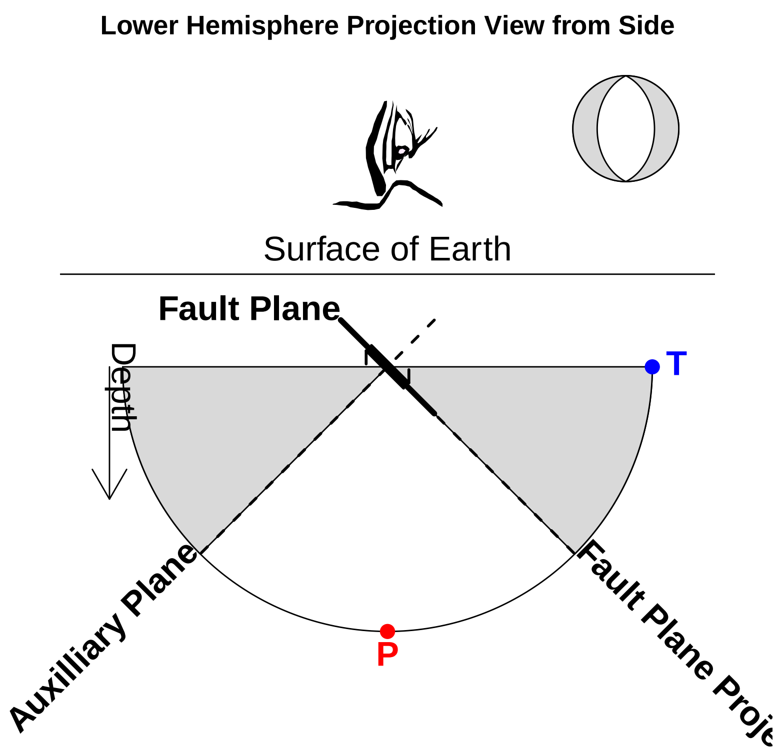


Figure 1: Cross section of focal mechanism in earth

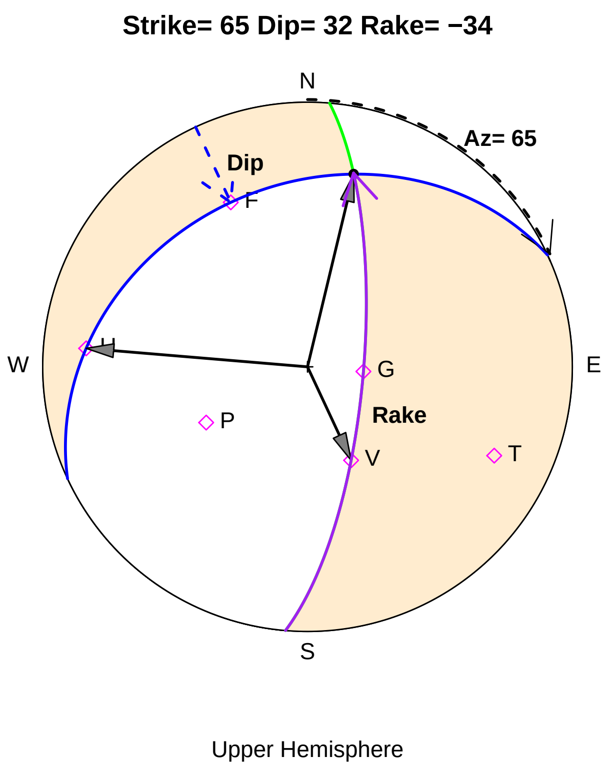


Figure 2: Sample focal mechanism with mark up for teaching purposes.

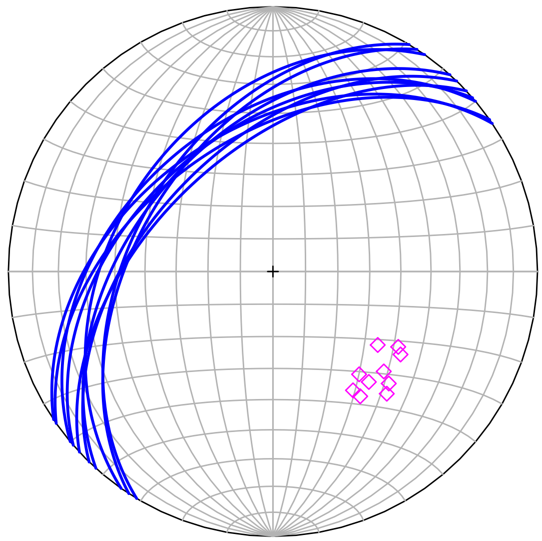
```
Vector 2: [1]  335   58
P-axis: [1]  61.16  54.02
T-axis: [1]  295.46   22.96
```

and, since a plotting function has been defined for the MEC structure, the result can be graphically viewed with,

```
> plotMEC(mc, detail = 2, up = FALSE)
```

as shown in Figure 2. The codes presented here can obviously be used to plot poles and fault planes on the focal sphere as commonly presented in summaries of geological presentations of fault strike-dip data, for example the following code will plot ten (random) poles and the corresponding fault planes:

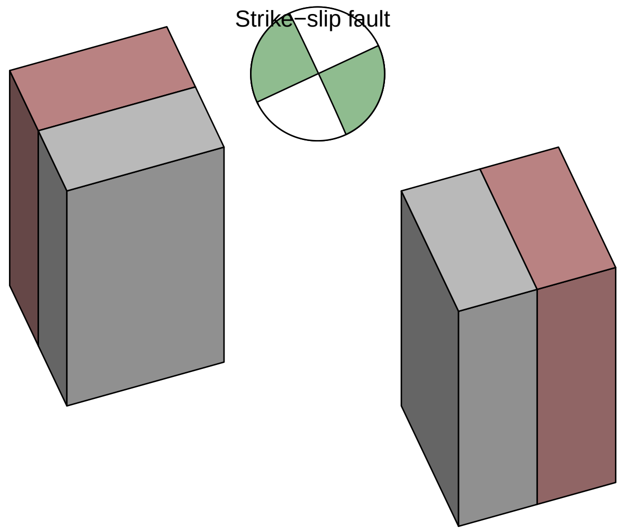
```
> K = 10
> rakes = runif(K, 30, 60)
> dips = runif(K, 40, 55)
> strikes = runif(K, 25, 75)
> net(add = FALSE)
> for (i in 1:K) {
+     mc = CONVERTSDR(floor(rakes[i]), floor(dips[i]), floor(strikes[i]))
+     LP1 = lowplane(mc$M$az1 - 90, mc$M$d1, col = "blue", UP = TRUE)
+     U = focpoint(mc$V$az, mc$V$dip, col = 6, lab = "", UP = TRUE)
+ }
```



here the net() function plots the equal-area stereonet and lowplane() and focpoint() plot planes and poles on the stereonet respectively.

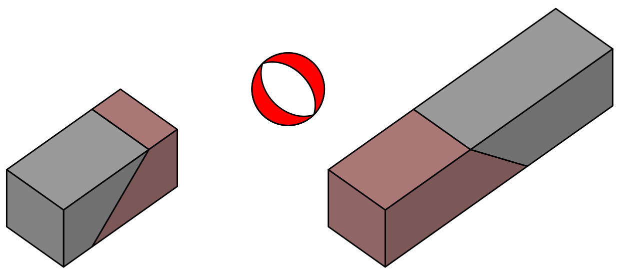
The following code shows how the focal mechanisms are interpreted by a geologist for three end-member cases. These figures can be animated for student easier understanding of faulting in an interactive R session.

```
> opar <- par(no.readonly = TRUE)
> par(MFA = c(1, 3))
> par(mas = c(0.1, 0.1, 0.2, 0.1))
> anim = 0
> strikeslip.fault(anim = anim, Light = c(45, 90))
> MFOC1 = SDRfoc(65, 90, 1, u = FALSE, ALIM = c(-1, -1, +1, +1),
+     PLOT = FALSE)
> Fcol1 = foc.color(foc.icolor(MFOC1$rake1), pal = 1)
> justfocXY(MFOC1, fcol = Fcol1, 0.5, 0.7, size = c(0.4, 0.4))
> mtext("Strike-slip fault", side = 3, line = -1.5)
```

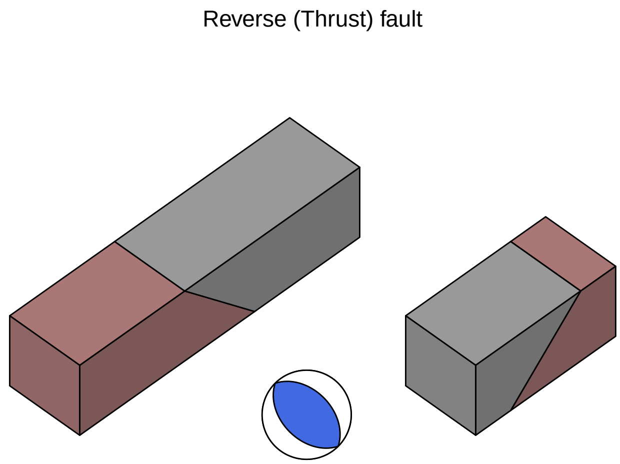



```
> normal.fault(45, anim = anim, KAPPA = 4, Light = c(-20, 80))
> MFOC2 = SDRfoc(135, 45, -90, u = FALSE, ALIM = c(-1, -1, +1,
+     +1), PLOT = FALSE)
> Fcol2 = foc.color(foc.icolor(MFOC2$rake1), pal = 1)
> justfocXY(MFOC2, fcol = Fcol2, 0.5, 1, size = c(0.45, 0.45))
> mtext("Normal fault", side = 3, line = -1.5)
```

Normal fault



```
> thrust.fault(anim = anim, KAPPA = 4, Light = c(-20, 80))
> MFOC3 = SDRfoc(135, 45, 90, u = FALSE, ALIM = c(-1, -1, +1, +1),
+     PLOT = FALSE)
> Fcol3 = foc.color(foc.icolor(MFOC3$rake1), pal = 1)
> justfocXY(MFOC3, fcol = Fcol3, 0, -1, size = c(0.45, 0.45))
> mtext("Reverse (Thrust) fault", side = 3, line = -1.5)
> par(opar)
```



4 Radiation Patterns

The beachball representation of earthquake focal mechanisms is actually a simplification of the P-wave radiation pattern for a double couple earthquake. The full radiation patterns are usually not plotted for standard seismological investigation but they can be useful for extracting details of seismic radiation that are usually overlooked. In RFOC an option for plotting the radiation patterns for all three of the P, SV and SH waves is available as shown in Figure 3. In RFOC conventions as described in are adhered to. One advantage of using an R package like RFOC for calculating radiation amplitudes is that one can extract the predicted amplitudes of the radiate waves and compare with observations on seismograms. This approach was used by to relate radiation patterns and reflections of waves of an interface in a geothermal field.

The code to produce the radiation pattern display first sets up a nice color palette with two simple functions and then calls the radiation routines.

```
> tomo.colors <- function(n, alpha = 1) {
+     if ((n <- as.integer(n[1])) > 0) {
```

```
+         k <- n%/%2
+         h <- c(0/12, 2/12, 8/12)
+         s <- c(1, 0, 1)
+         v <- c(0.9, 0.9, 0.95)
+         c(hsv(h = seq.int(h[1], h[2], length = k), s = seq.int(s[1],
+             s[2], length = k), v = seq.int(v[1], v[2], length = k),
+             alpha = alpha), hsv(h = seq.int(h[2], h[3], length = n -
+             k + 1)[-1], s = seq.int(s[2], s[3], length = n -
+             k + 1)[-1], v = seq.int(v[2], v[3], length = n -
+             k + 1)[-1], alpha = alpha))
+     }
+     else character(0)
+ }
> Gcols <- function(plow = 10, phi = 10, N = 100, pal = "rainbow",
+     mingray = 0.5) {
+     if (missing(plow)) {
+         plow = 10
+     }
+     if (missing(phi)) {
+         phi = 10
+     }
+     if (missing(N)) {
+         N = 100
+     }
+     if (missing(pal)) {
+         pal = "rainbow"
+     }
+     if (missing(mingray)) {
+         mingray = 0.5
+     }
+     nlow = floor(plow * N/100)
+     nhi = floor(phi * N/100)
+     LOW = grey(seq(from = mingray, to = 1, length = nlow))
+     HI = grey(seq(from = mingray, to = 1, length = nhi))
+     K = N - nlow - nhi
+     FUN = match.fun(pal)
+     Z = FUN(K)
+     return(c(LOW, Z, HI))
+ }
> mc = CONVERTSDR(65, 32, -34)
> MEC = MRake(mc$M)
> MEC$strike = mc$strike
> MEC$dipdir = mc$dipdir
> MEC$dip = mc$dip
> MEC$rake = mc$rake
> MEC$UP = FALSE
```

```
> mycol = Gcols(plow = 0, phi = 0, N = 100, pal = "tomo.colors")
> par(mfrow = c(1, 3))
> par(mai = c(0.5, 0.1, 0.5, 0.1))
> radiateP(MEC, col = mycol)
> text(0, 1, labels = "P-wave  radiation, Lower Hemisphere", pos = 3,
+     cex = 1.5)
> radiateSV(MEC, col = mycol)
> text(0, 1, labels = "SV-wave  radiation, Lower Hemisphere", pos = 3,
+     cex = 1.5)
> radiateSH(MEC, col = mycol)
> text(0, 1, labels = "SH-wave  radiation, Lower Hemisphere", pos = 3,
+     cex = 1.5)
```

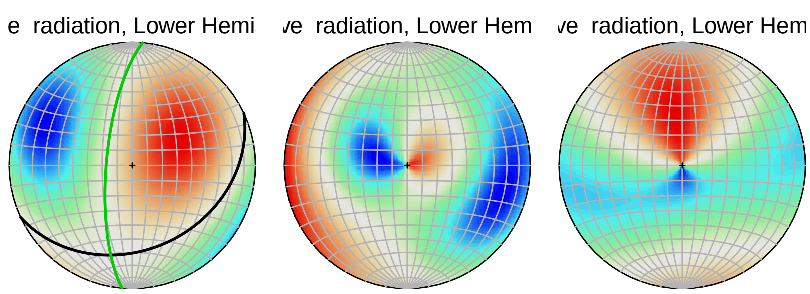


Figure 3: Radiation Patterns

5 Map Views

Once focal mechanisms are determined for each earthquake they can be plotted in map view using standard projections as a set of beach balls (Figure 4). The beach balls relate the nature of changing stress in the earth during earthquake swarms. In RFOC they are color coded to indicate the sense of the faults during rupture. Focal mechanism plots can be scaled and plotted on top of maps to indicate spatial distribution of earthquake rupture patterns, stress variations and alignment of faults. In a flexible environment like R one can quickly develop complex graphical representations that illustrate geological correlation. In this case I am just plotting the location with simple geographic (longitude, latitude) values. As such these will not be correctly projected, of course, since in the far north the value of a latitude in degrees is not the same as a longitude. Please consult package GEOmap for details on how to plot the focal mechanisms with maps properly projected.

```
> data(KAMCORN)
> plot(range(KAMCORN$LON), range(KAMCORN$LAT), type = "n", xlab = "LON",
+     ylab = "LAT", asp = 1)
> for (i in 1:length(KAMCORN$LAT)) {
+     mc = CONVERTSDR(KAMCORN$STRIKE[i], KAMCORN$DIP[i], KAMCORN$RAKE[i])
+     MEC <- MRake(mc$M)
+     MEC$UP = FALSE
+     Fcol <- foc.color(foc.icolor(MEC$rake1), pal = 1)
+     justfocXY(MEC, x = KAMCORN$LON[i], y = KAMCORN$LAT[i], size = c(0.5,
+         0.5), fcol = Fcol, xpd = FALSE)
+ }
```

One difficulty in plotting numerous focal mechanisms as beachballs is that they may overlap or othewise obscure important information on the underlying geographical map. RFOC provides an alternative, succinct representation that plots only the primary fault plane and the associated slip vector(Figure 5).

```
> plot(range(KAMCORN$LON), range(KAMCORN$LAT), type = "n", xlab = "LON",
+     ylab = "LAT", asp = 1)
> for (i in 1:length(KAMCORN$LAT)) {
+     mc = CONVERTSDR(KAMCORN$STRIKE[i], KAMCORN$DIP[i], KAMCORN$RAKE[i])
+     MEC <- MRake(mc$M)
+     MEC$UP = FALSE
+     Fcol <- foc.color(foc.icolor(MEC$rake1), pal = 1)
+     nipXY(MEC, x = KAMCORN$LON[i], y = KAMCORN$LAT[i], size = c(0.5,
+         0.5), fcol = Fcol)
+ }
```

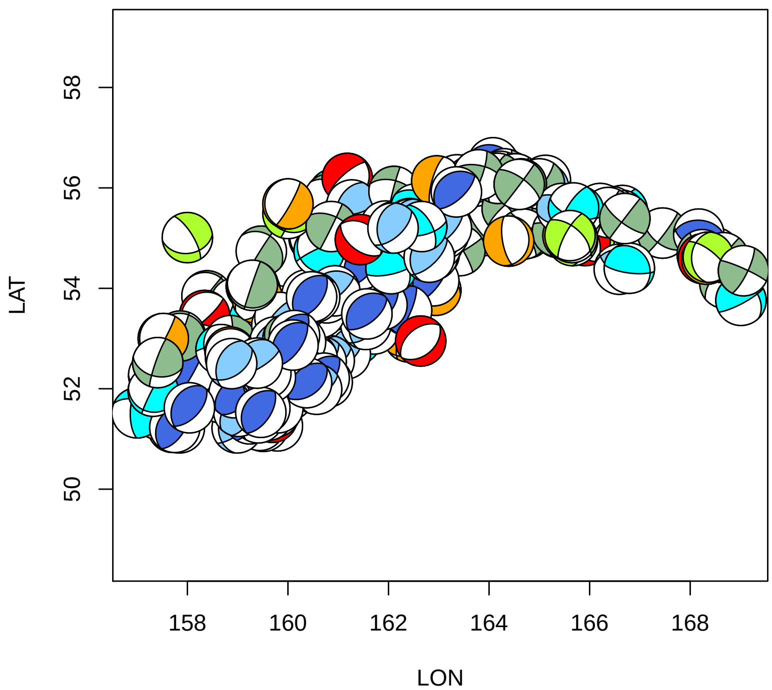


Figure 4: Beachball focal mechanisms plotted at Kamchatka-Aleutian junction.

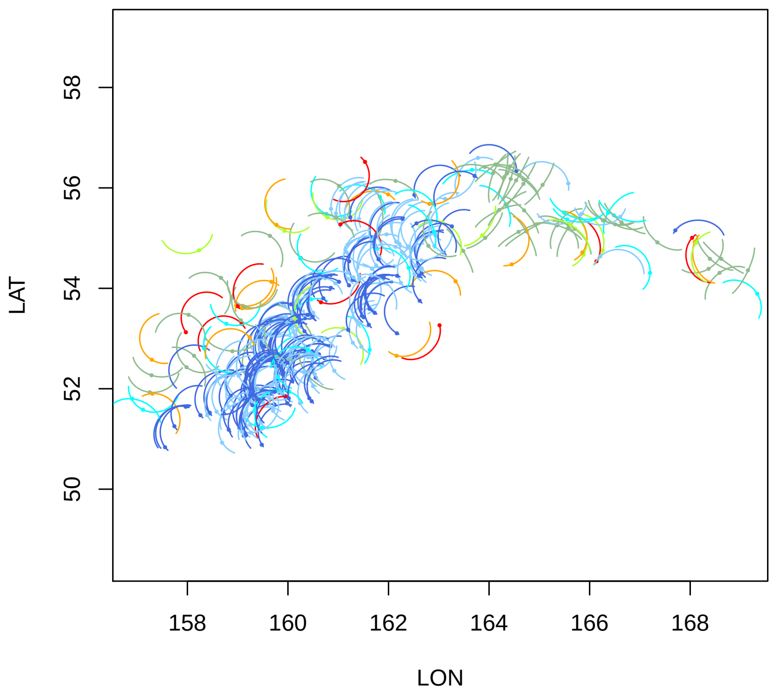


Figure 5: Plane-Slip focal mechanisms plotted at Kamchatka-Aleutian junction.

6 Summary Representations

Often there are too many focal planes to deal with reasonably and summary statistics/graphics are required. In this case a selected set of focal solutions can be presented graphically via two kinds of plots in RFOC: a stereo-net of the P-T axes projections (Figure 6) and a ternary plot (Figure 7) of all the focal mechanisms in the selection categorized by pure strike-slip, normal or reverse faulting. Here I am presenting the accumulated set of focal mechanisms distributed over the Aleutian-Kamchatka Arcs from 1376 earthquakes extracted from the Harvard CMT catalogue (http://www.seismology.harvard.edu/projects/CMT, 1976-2005). Density plots of these distributions hi-lite average orientations of P and T axes and graphically indicate the variance of the distributions on the sphere (Figure 8).

```
> net()
> PZZ = focpoint(PKAM$Paz, PKAM$Pdip, col = "red", pch = 3, lab = "",
+     UP = FALSE)
> TZZ = focpoint(PKAM$Taz, PKAM$Tdip, col = "blue", pch = 4, lab = "",
+     UP = FALSE)
> text(0, 1.04, labels = "P&T-axes Projected", font = 2, cex = 1.2)
> legend("topright", c("P", "T"), col = c("red", "blue"), pch = c(3,
+     4))
```

Geographically distributed ternary plots can be generated by dividing a target region into smaller subregions and plotting ternary and/or spherically contoured plots for each subset. This approach provides an easy way to visualize how fault zones vary spatially in complex geology where data sets are large and heterogeneous. RFOC provides an easy way to associate a subset of focal data with a geographic location, and position the stereonet or ternary plot accordingly. Once a map is plotted, subsectioned and ternary plots are created, they can be plotted on the map by the same routine for plotting one Ternary diagram:

```
> fcols = foc.color(PKAM$IFcol, 1)
> PlotTernfoc(PKAM$h, PKAM$v, x = 0, y = 0, siz = 1, fcols = fcols,
+     add = FALSE, LAB = TRUE)
> MFOC3 = SDRfoc(135, 45, 90, u = FALSE, ALIM = c(-1, -1, +1, +1),
+     PLOT = FALSE)
> Fcol3 = foc.color(foc.icolor(MFOC3$rake1), pal = 1)
> MFOC2 = SDRfoc(135, 45, -90, u = FALSE, ALIM = c(-1, -1, +1,
+     +1), PLOT = FALSE)
> Fcol2 = foc.color(foc.icolor(MFOC2$rake1), pal = 1)
> MFOC1 = SDRfoc(65, 90, 1, u = FALSE, ALIM = c(-1, -1, +1, +1),
+     PLOT = FALSE)
> Fcol1 = foc.color(foc.icolor(MFOC1$rake1), pal = 1)
> justfocXY(MFOC3, fcol = Fcol3, 1.2, -0.9, size = c(0.1, 0.1))
> justfocXY(MFOC2, fcol = Fcol2, -1.2, -0.9, size = c(0.1, 0.1))
```

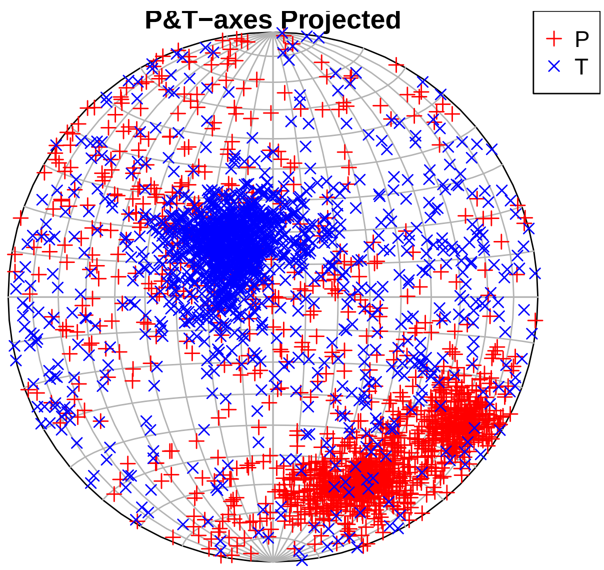


Figure 6: Summary of P-T axes from Kamchatka-Aleutian Arc

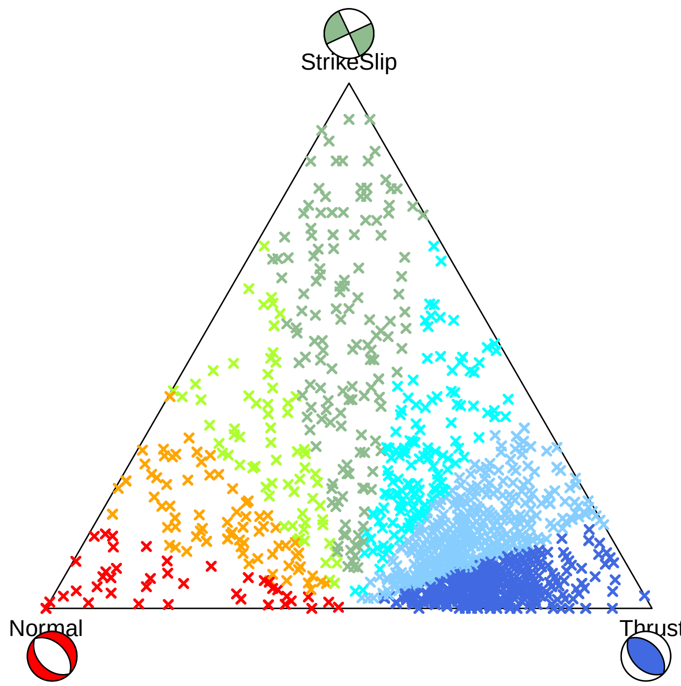


Figure 7: Ternary Plot of focal mecahnisms

```
> justfocXY(MFOC1, fcol = Fcol1, 0, 1.414443 + 0.2, size = c(0.1,
+     0.1))
```

The P and T axes can be plotted as an image and contoured.

```
> KP = kde2d(PZZ$x, PZZ$y, n = 50, lims = c(-1, 1, -1, 1))
> KT = kde2d(TZZ$x, TZZ$y, n = 50, lims = c(-1, 1, -1, 1))
> opar <- par(no.readonly = TRUE)
> par(mfrow = c(1, 3))
> par(mai = c(0.2, 0, 0.2, 0))
> CC = PLTcirc(PLOT = FALSE, add = FALSE, ndiv = 36, angs = c(-pi,
+     pi))
> image(KP$x, KP$y, KP$z, add = TRUE, col = terrain.colors(100))
> antipolygon(CC$x, CC$y, col = "white")
> net(add = 1)
> focpoint(PKAM$Paz, PKAM$Pdip, col = "red", pch = 3, lab = "",
```

```
+      UP = FALSE)
> text(0, 1.04, labels = "P-axes 2D Density", font = 2, cex = 1.2)
> CC = PLTcirc(PLOT = FALSE, add = FALSE, ndiv = 36, angs = c(-pi,
+      pi))
> image(KT$x, KT$y, KT$z, add = TRUE, col = terrain.colors(100))
> antipolygon(CC$x, CC$y, col = "white")
> net(add = 1)
> focpoint(PKAM$Taz, PKAM$Tdip, col = "blue", pch = 4, lab = "",
+      UP = FALSE)
> text(0, 1.04, labels = "T-axes 2D Density", font = 2, cex = 1.2)
> CC = PLTcirc(PLOT = FALSE, add = FALSE, ndiv = 36, angs = c(-pi,
+      pi))
> image(KP$x, KP$y, KP$z, add = TRUE, col = terrain.colors(100))
> net(add = 1)
> contour(KT$x, KT$y, KT$z, add = TRUE, lwd = 1.2)
> antipolygon(CC$x, CC$y, col = "white")
> text(0, 1.04, labels = "Combined P-T 2D Density", font = 2, cex = 1.2)
> par(opar)
```

The summary plots presented by RFOC can just as well be distributed spatially to illustrate smoothed or averaged properties over large geographic regions.

A geographic region is commonly broken down into distinct areas and density plots show how the stress is distributed spatially or temporally over that region. First we divide the region into blocs that have 5 or more earthquakes.

```
> x = fmod(PKAM$LONS, 360)
> y = PKAM$LATS
> plot(x, y, asp = 1, type = "p", xlab = "LON", ylab = "LAT")
> u = par("usr")
> RI = RectDense(x, y, icut = 5, u = u, ndivs = 10)
> rect(RI$icorns[, 1], RI$icorns[, 2], RI$icorns[, 3], RI$icorns[,
+      4], col = NA, border = "blue")
```

The ternary plots can then be added by looping through the individual sections.

```
> Fcol = foc.color(PKAM$IFcol, pal = 1)
> i = 1
> sizy = RI$icorns[i, 4] - RI$icorns[i, 2]
> sizx = RI$icorns[i, 3] - RI$icorns[i, 1]
> siz = 0.5 * min(c(sizy, sizx))
> plot(x, y, asp = 1, type = "p", xlab = "LON", ylab = "LAT")
> u = par("usr")
> RI = RectDense(x, y, icut = 5, u = u, ndivs = 10)
> rect(RI$icorns[, 1], RI$icorns[, 2], RI$icorns[, 3], RI$icorns[,
+      4], col = NA, border = "blue")
> for (i in 1:length(RI$ipass)) {
```

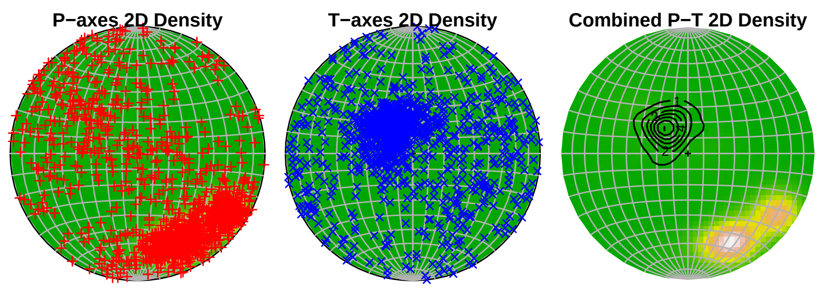


Figure 8:

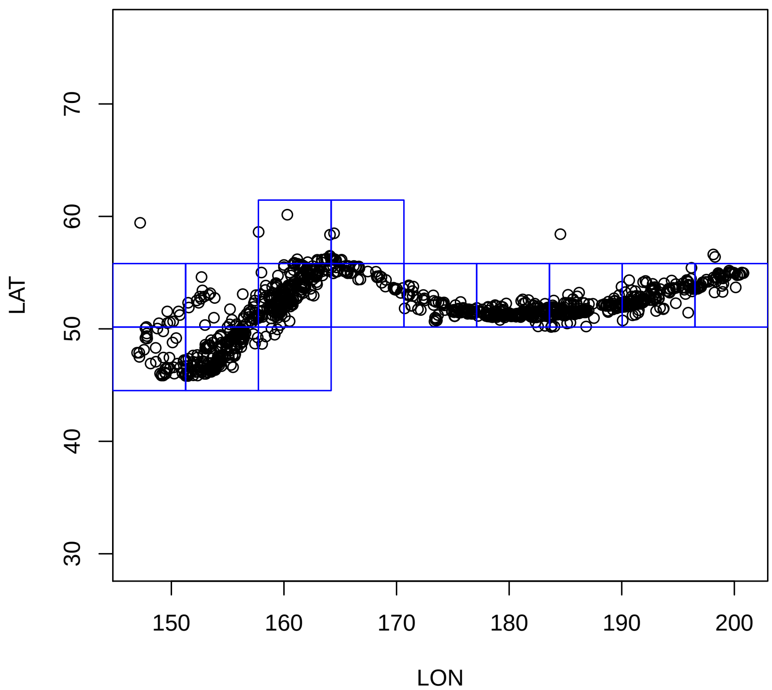


Figure 9:

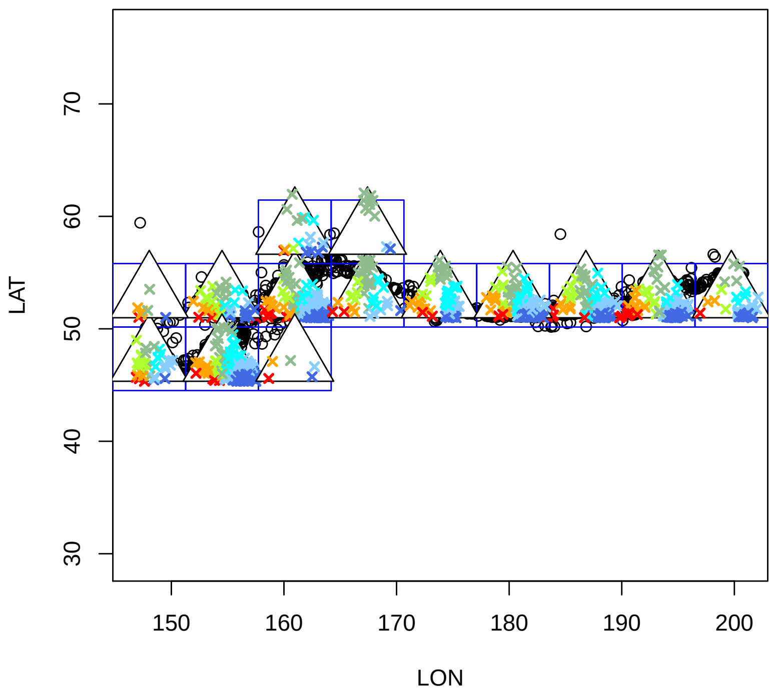


Figure 10: P and T axes as ternary plots distributed across Aleutian Arc

```
+     flag = x > RI$icorns[i, 1] & y > RI$icorns[i, 2] & x < RI$icorns[i,
+         3] & y < RI$icorns[i, 4]
+     jh = PKAM$h[flag]
+     jv = PKAM$v[flag]
+     PlotTernfoc(jh, jv, x = mean(RI$icorns[i, c(1, 3)]), y = mean(RI$icorns[i,
+         c(2, 4)]), siz = siz, fcols = Fcol[flag], add = TRUE)
+ }
```

Then we can also plot orientations of P and T-axes by applying the same approach:

```
> x = fmod(PKAM$LONS, 360)
> y = PKAM$LATS
> plot(x, y, asp = 1, type = "p", xlab = "LON", ylab = "LAT")
> u = par("usr")
> KPspat = matrix(NA, nrow = length(RI$ipass), ncol = 10)
```

```
> KTspat = matrix(NA, nrow = length(RI$ipass), ncol = 10)
> colnames(KTspat) = c("x", "y", "n", "Ir", "Dr", "R", "K", "S",
+     "Alph95", "Kappa")
> colnames(KPspat) = c("x", "y", "n", "Ir", "Dr", "R", "K", "S",
+     "Alph95", "Kappa")
> for (i in 1:length(RI$ipass)) {
+     flag = x > RI$icorns[i, 1] & y > RI$icorns[i, 2] & x < RI$icorns[i,
+         3] & y < RI$icorns[i, 4]
+     paz = PKAM$Paz[flag]
+     pdip = PKAM$Pdip[flag]
+     taz = PKAM$Taz[flag]
+     tdip = PKAM$Tdip[flag]
+     ax = mean(RI$icorns[i, c(1, 3)])
+     ay = mean(RI$icorns[i, c(2, 4)])
+     siz = (RI$icorns[1, 3] - RI$icorns[1, 1])/2.5
+     PlotPTsmooth(paz, pdip, x = ax, y = ay, siz = siz, border = NA,
+         bcol = "white", LABS = FALSE, add = FALSE, IMAGE = TRUE,
+         CONT = FALSE)
+     PlotPTsmooth(taz, tdip, x = ax, y = ay, siz = siz, border = NA,
+         bcol = "white", LABS = FALSE, add = TRUE, IMAGE = FALSE,
+         CONT = TRUE)
+     ALPH = alpha95(paz, pdip)
+     n = length(paz)
+     KPspat[i, ] = c(ax, ay, n, ALPH$Ir, ALPH$Dr, ALPH$R, ALPH$K,
+         ALPH$S, ALPH$Alph95, ALPH$Kappa)
+     ALPH = alpha95(taz, tdip)
+     KTspat[i, ] = c(ax, ay, n, ALPH$Ir, ALPH$Dr, ALPH$R, ALPH$K,
+         ALPH$S, ALPH$Alph95, ALPH$Kappa)
+ }
```

7 Conclusion

In summary, I have present one aspect of the RFOC package that will be useful for earth scientists who work with earthquakes and faults. The stereo-net analysis is completely general and can be used for graphical illustration of any process that is distributed on a sphere. The graphical representations of spherical data can be plotted spatially to indicate patterns of variation relevant to earth processes and hazard reduction in earthquake prone regions. Summaries of large numbers of earthquake pressure or tension axes can be graphically displayed as sets of ternary diagrams or density plots in stereo-graphic projections. These can further be plotted on maps to show spatial variations important for earthquake analysis, hazard mitigation and volcano dynamics.

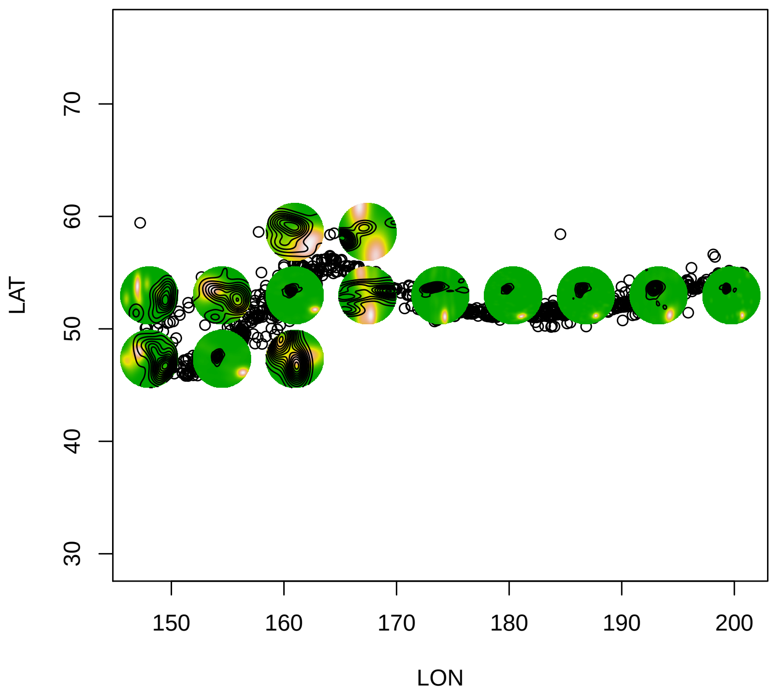


Figure 11: P and T axes stereonet projections distributed across Aleutian Arc