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User's Manual

KAGDOM v1.0

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1 What Is This Document?

This document serves as a brief introduction to the KAGDOM software. Here, I will try to provide a background on if/how/why using the concept of Kagan angle is helpful. I will also provide a short overview of the software – which admittedly is very simple.

While some of the details in the programs are discussed here, I have put most of the details as comments in the original codes.

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2 Comparing Beachballs

Earthquake focal mechanism is often shown with beachballs. This graphical representation of focal mechanism is especially helpful when comparing earthquakes. For example, Fig. 1 shows the distribution of global shallow (crustal) seismicity from the CMT catalog (Ekström et al., 2012). In Fig. 1, one can visually compare the mechanisms of earthquakes that have occurred throughout the globe.

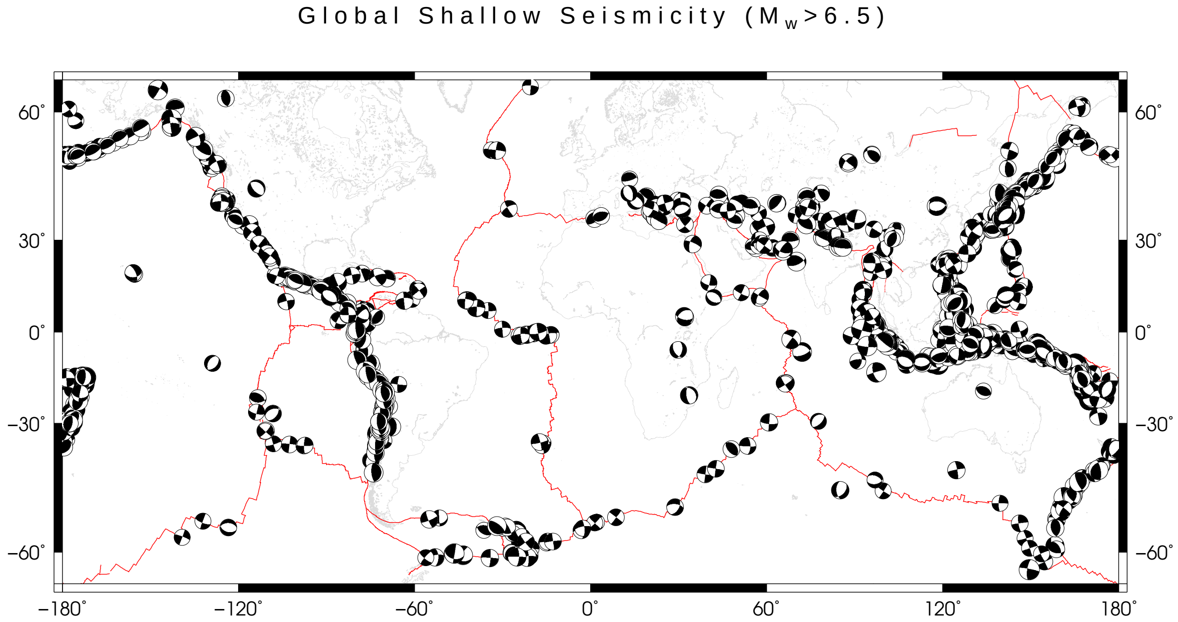


Figure 1: Global distribution of focal mechanism for shallow ($h \leq 40$ km) earthquakes from the CMT catalog (Ekström et al., 2012). Red and gray lines show plate boundaries and continents.

However, visual comparison is extremely qualitative and does not provide an "exact" difference between two given mechanisms. For example, while by looking at the mechanisms in Fig. 2 we can – with certainty – conclude that they represent earthquakes with different mechanism, we cannot comment on *exactly how much* they are different.

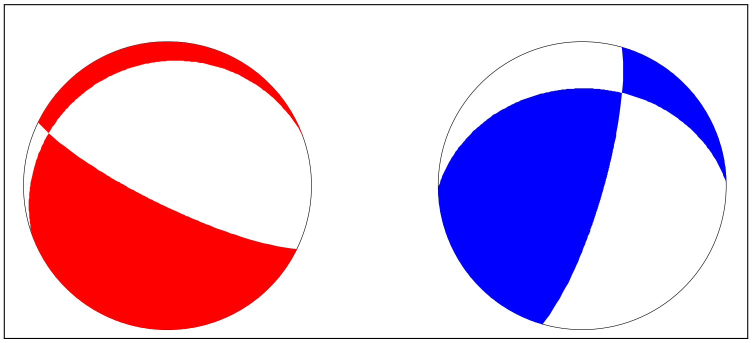


Figure 2: Focal mechanisms for *mostly normal* (left) and *mostly thrust* (right) events, both with strike-slip components.

As a result, several studies have tried to quantify this difference through various means such as accumulating ternary diagrams using the T, B and P axes of beachballs (Frohlich & Apperson, 1992), histograms of plunge vectors (Isacks & Molnar, 1971), and defining a rotation angle between two given beachballs (Kagan, 1991).

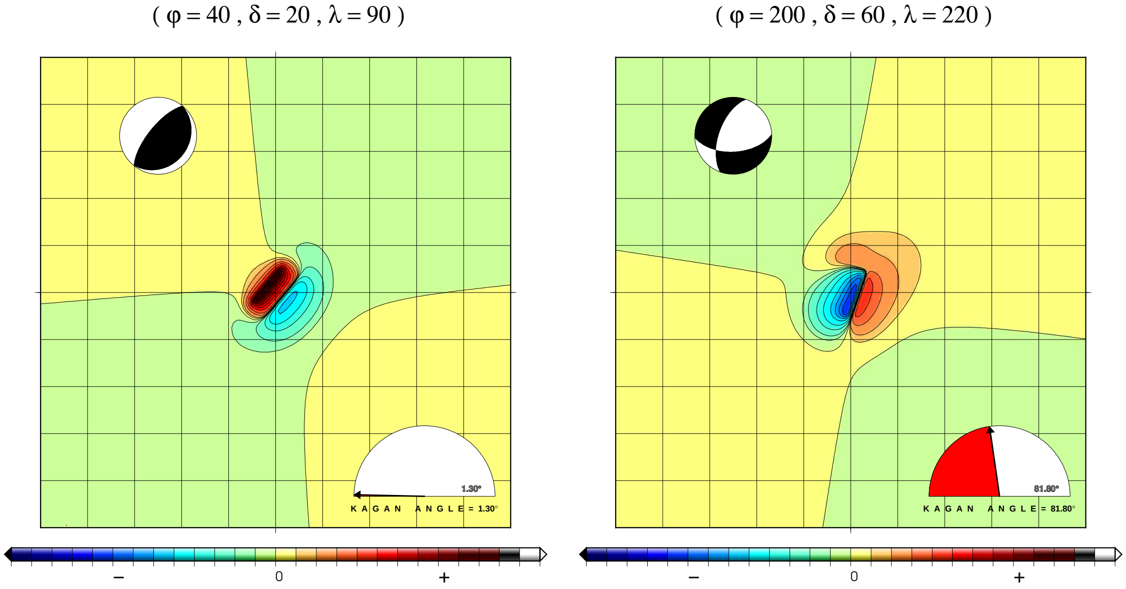
Among such methods, the latter, known as *Kagan angle*, is more straightforward to use as it is geometrically more intuitive, and also provides a single value for the difference between two given mechanisms.

2.1 Kagan Angle

While earthquakes vary in their mechanisms, they all can be shown using the same idea: earthquake source mechanisms are rotated versions of the same beachball (Fig. 3). The orientation of the beachball is determined by the three fault angles of strike (ϕ), dip (δ), and slip (λ), and therefore various permutations of fault angle results in different orientations/rotations of the same beachball (e.g. Okal, 2011).

To describe the spatial rotation necessary to get from a beachball to another, Kagan (1991) proposed an angle ranging between 0° and 120° . For example, the difference between the two mechanisms in Fig. 2 can be expressed as a 85° Kagan angle. This means that an 85° rotation of the mechanism on left in Fig. 2 will produce the mechanism on the right in the same figure. Fig. 4 shows the Kagan angle between two different focal mechanisms.

Figure 3: Three basketballs identically painted to represent beachballs. Orientations of the same beachball can result in (from left to right): normal, strike-slip, and thrust mechanisms.



(a) (b)

Figure 4: (a) and (b) show two different earthquake mechanisms along with their corresponding surface deformations as measures of how different they look on the ground. On the top left of each panel are shown the representative beachball, and on bottom right are gauges showing the Kagan angle between each mechanism and (a) – the gauge in (a) is the Kagan angle between the mechanism in (a) and itself and is therefore showing *zero*.

3 Kagan Angle & Tectonics

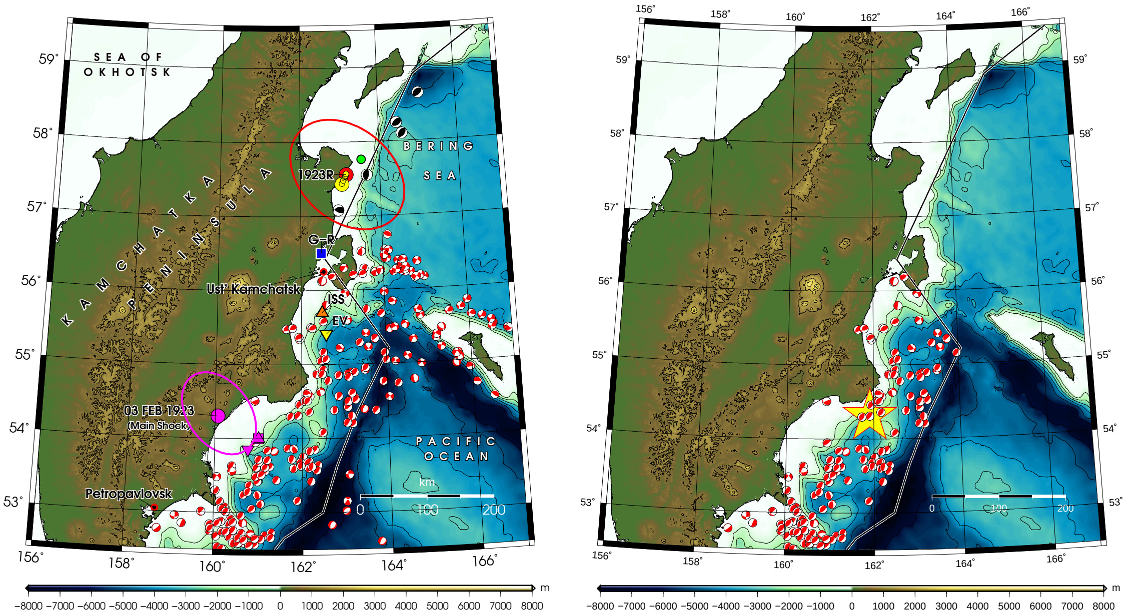
3.1 Conforming to the Background Seismicity

Often times it is very useful to check if the proposed mechanism for an earthquake is in agreement with a dataset, say the general trend of source mechanisms in the region. A suitable tool to achieve this, is the Kagan angle. One can easily calculate the angles between the available focal mechanisms for the region with respect to the proposed beachball and measure the scatter. Obviously, a large scatter would mean that the orientations of focal mechanisms do not focus on the fixed mechanism.

For example, in looking at the seismicity of Kamchatka (Fig. 5(a)), one may suspect that the earthquakes to the west of the Pacific Ocean-Eurasia boundary are mostly caused by the subduction process and therefore would have similar mechanisms.

It is easy to check if a specific event, say the 13 April 1923 earthquake, was caused by the same mechanism. This is especially helpful if a good mechanism is not available for the event. In such cases, various "guesses" for the mechanism of the event in question can be quantitatively compared to the background regime to find the one that is the best match.

This can be easily achieved using the concept of Kagan angle. One can isolate the events in eastern Kamchatka (Fig. 5(b)) and then calculate the Kagan angle between each of these events and the selected mechanism for the earthquake in question. As shown in Fig. 6, a proposed mechanism of ($\phi = 202°, \delta = 23°, \lambda = 74°$) is in good agreement with the background regime as the calculated Kagan angles between this mechanism and the isolated events are clustered between only 10° –15° , with a median of 15.3° .



(a) (b)

Figure 5: (a) Seismicity of Kamchatka; (b) events associated with the subduction. The yellow star represents the epicenter of the 1923 event.

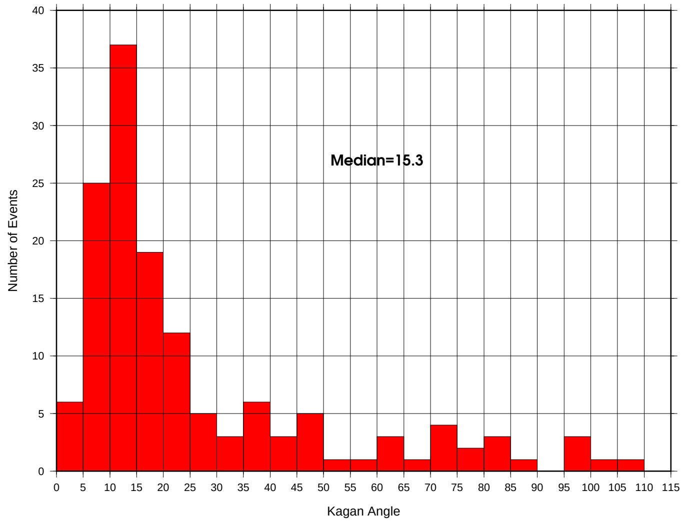


Figure 6: A histogram of the Kagan angles between a proposed mechanism for the 13 April 1923 and the background events (see Fig. 5(b)). Concentration of the angles between 10° –15° shows that the proposed mechanism is in good agreement with the local tectonic regime.

3.2 Dominant Focal Mechanism

In determining the dominant faulting regime (compression, extension, or transform) in a region, or to find the orientations of stress axes in a dataset, studying and quantifying the *dominant earthquake mechanism* can be extremely helpful. It is customary to check if the available focal mechanisms (or beachballs) for the earthquakes in a region have similar spatial orientations.

Kagan angle provides a robust tool to quantitatively compare the beachballs for earthquake mechanisms. From a list of focal geometries (strike,dip,slip), one can compare the mechanism of each event with the rest, and create auxiliary lists of Kagan angles for each earthquake. Then, by calculating the the scatter (standard deviation) of each auxiliary list and picking the lowest scatter, the corresponding event will be the dominant focal mechanism. This is due to the fact that the rest of focal geometries will need smallest angles to convert into the selected mechanism.

For example, by looking at the CMT catalog of southwestern Iran (red beachballs in Fig. 7), we would immediately notice the dominant compressional regime due to the prevalent thrust component of the source geometries. This is due to the accumulated compressional stress from the continental collision between the Arabian and Eurasian plates (white arrows in Fig. 7).

In order to quantify the aforementioned prevalence, by following through the above algorithm we can calculate a dominant thrust mechanism as shown in Fig. 7 with a blue beachball. This is particularly interesting as the calculated mechanism seems very different from the one calculated as a median of the dataset.[1] Also, it is noteworthy that the median mechanism does not agree with the tectonic regime of the region.

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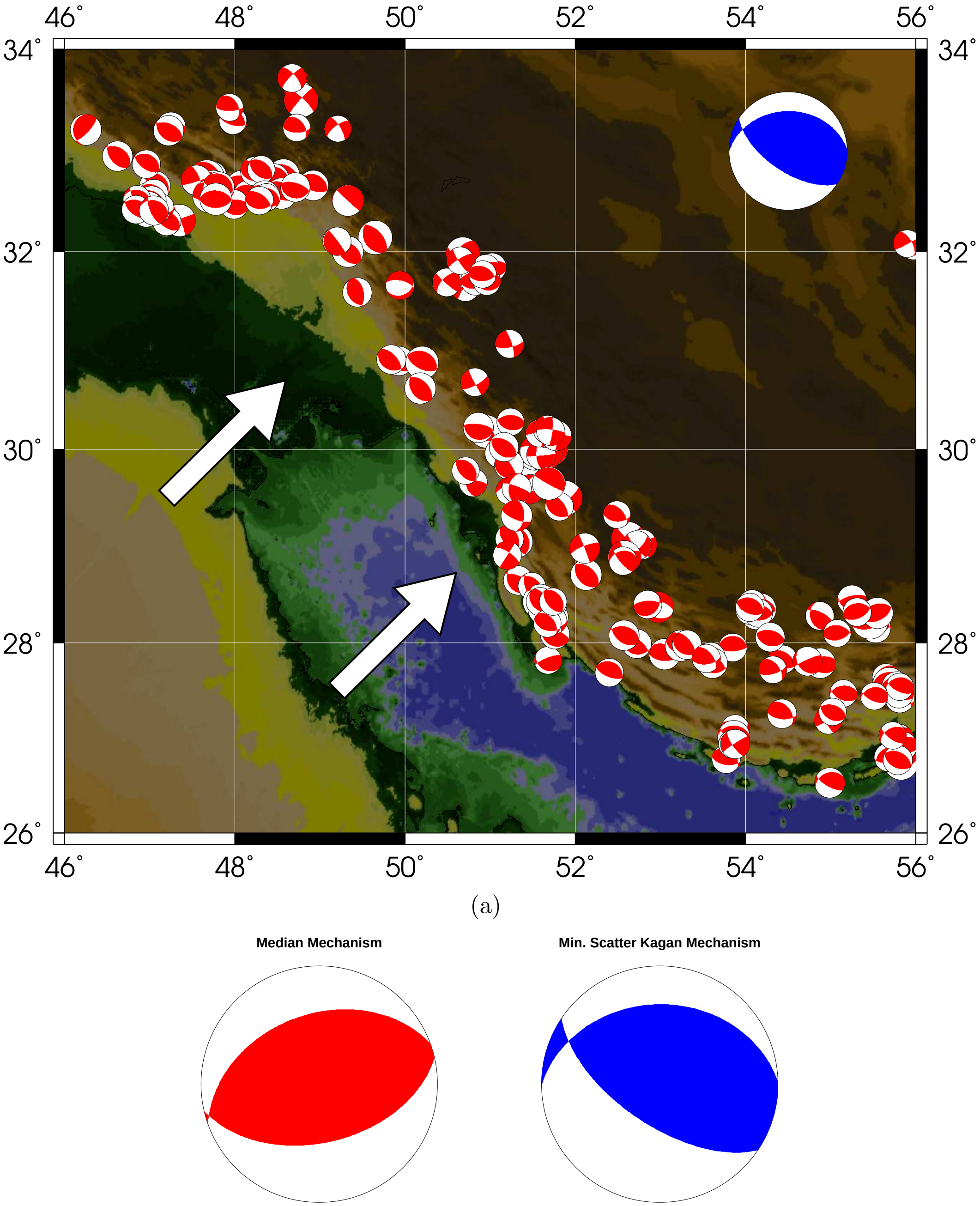
[1] By calculating the medians of strike, dip, and slip angles separately.



(a)

(b)

Figure 7: (a) The CMT solutions for earthquakes in southwestern Iran. The calculated dominant mechanism is shown with a blue beachball on the top-left. The white arrows show the predominant convergence between Eurasia and Arabia; (b) The median (red) and Kagan (blue) mechanisms calculated as dominant focal geometries. The two beachballs are at a 49.5° angle with each other.

4 KAGDOM

The KAGDOM package is a set of FORTRAN codes and shell scripts for calculating the dominant focal geometry in a dataset. This is done using two different methods:

1. Algebraic median of the focal mechanisms.
2. The algorithm described in section 3.2: the software calculates the Kagan angles between each mechanism and the rest of the population and finds the scatter in each set; the beachball with minimum scatter will be the dominant mechanism.

At the end, the results are graphically compared.

4.1 Components

After extracting the distribution and successfully compiling the programs,[2] the binary executables are stored in the `bin/` directory. A script to plot the results is included in the `shell/` directory which is useful to make customized plots.

The main script (`kagdom`) is located in the main directory. In principle, you will only need to deal with this script to use the software. However, you may want to modify the individual programs (in FORTRAN) to tailor the package to your needs.

4.2 Running KAGDOM

To used the program you will need a CMT event file with strike, dip, and slip angles of the first focal plane on the 4th, 5th, and 6th columns.[3]

If you have the event file, simply make a subdirectory with an arbitrary name into which you should copy the event file. Then switch to the new directory and run

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[2] For instructions on compiling the programs, please see the README file included in the main directory.

[3] Such a file is the standard output of my CMT catalog search program, CATCMT, which is not included in this package.

the main script:

```
../kagdom
```

The main outputs from the program are:

- `kmin.out`: Dominant mechanism (ϕ, δ, λ) calculated using the procedure explained above, along with its scatter (standard deviation), and an index. The index number belongs to the n^{th} event in the catalog that best represents the dominant mechanism.[4]
- `focmed.out`: Median mechanism (ϕ, δ, λ)
- `focal.ps`, `focal.eps`, `focal.jpg`: Various formats of the final graphics illustrating the two mechanisms.
- `kagan.dat.XXXXX`: Auxiliary lists containing Kagan angles between the `XXXXX`$^{\text{th}}$ catalog event and the rest.

4.2.1 The Issue of Invalid Minima

A given list of focal geometries may include a particular event which is very different from the rest. In this case, all the other events in the catalog will have very large Kagan angles from this particular event. The result will be a sharp concentration (i.e. low scatter) of Kagan angles in the auxiliary list for the event in question. Therefore, in looking for the smallest scatter as a measure of the main trend, one may accidentally pick this outlier which has a sharp cluster of very large Kagan angles.

To avoid falling into this *invalid minimum*'s trap, we can set an empirical maximum threshold for the Kagan angle in our routines. In this version of the program, we have selected 45° as such a maximum.

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[4] This is the event with the least amount of scatter in its calculated Kagan angle from the rest.

4.2.2 Time

KAGDOM can be run on Desktop computers without any issues. However, it is important to keep in mind that running KAGDOM will take a while, especially for large catalogs, as the necessary computation time will be in the order of N^2 for a catalog with N events.

Typically, for a catalog of ~ 200 events, KAGDOM will take about a minute to run on a regular computer. This value will significantly increase for large catalogs with 1000+ earthquakes.

The timing issue can be resolved in the future by including the time-consuming loops within the FORTRAN programs instead of handling them in the shell scripts.

References

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