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THEORY OF EARTHQUAKE ORIGIN LOCATION AND ITS APPLICATION IN THE ETHIOPIAN WESTERN PLATEAU

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ABSTRACT

Earthquakes registered on the same day by a network of stations were assumed to come from the same source or event. Matrix equations were developed using simple geometry laws and standard empirical relationships governing tremors in Ethiopia. The solutions of these equations yielded 71 epicenters. The plot of the epicenters revealed two major sources, one a fault plane running from NW plane into NE plane and the other appears to be an area source in the SW plane. The mean value of epicenters located in the NE plane is (N 15.03^0, E 47.08^0) which is in the vicinity of Ethiopia and these epicenters can be designated as the sources of tremors that occurred in Ethiopia on 1 June 1961.

Key words: Earthquakes, Epicenters, Fault.

INTRODUCTION

An earthquake is a movement of the earth's crust that causes the ground to shake or vibrate. The earth's crust is made up of about 20 plates that are always moving, rubbing against each other. When the edges of two plates become jammed, tension builds up and a sudden movement of the plates relieves the tension.

A tension between two plates builds up and when it is finally released in an earthquake, it is transmitted to the surrounding areas in two waves. The first is the compression, or primary wave, which acts like a sound wave and creates a rumble or muted boom. This may be a warning to the inhabitants that a quake is coming. The secondary or shear, wave follows and this is the wave that causes damage. It passes through solids of the earth's crust, and in characteristic shape deformation moves the parts of the earth's crust through which it passes and thus shakes buildings/structures at the surface. The point within the earth's crust where the force is released is the earthquake focus. The epicenter is a point on the surface of the earth, which is directly above the seismic focus of an earthquake and where the tremor vibrations reach first.

Scientists now generally agree on what causes earthquakes and where they are most likely to occur. When they will happen is still a matter of continuing research. There are physical changes that are known to precede a quake. These changes include a shift in the angle or height of the ground surface, ionization of the air due to the electricity produced by internal pressures, the presence of radiation gas, vibrations, shifts in the earth's magnetic field, and the rise or fall of ground water.

Advanced electronic surveying methods using laser beams enable scientists to measure the rate at which the earth's crust is moving. Surveillance and the measure of radon gas released in fault areas seem to offer the most hope that scientists will be able to forecast earthquakes with great accuracy.

For accurate forecasts of earthquakes to save lives and properties, there is the need to know the fault lines or earthquake sources (sources of radon gas) and the rate of earth's crust movement. Several, groups such as, the International Seismological Center (ISC), Worldwide Standard Seismograph Network (WWSSN), United States Coast and Geodetic Survey (USCGS), etc. were introduced to measure and record information on the occurrences of earthquakes with the aim of providing lasting solution to earthquake source location problem, (Robert, 1970).

Nowadays these groups/systems are greatly assisted by computers and modern worldwide telecommunications. However, pre-computer records employed in the study of earthquakes need to be updated to give a comprehensive knowledge of the past and present seismic activity of a region.

One of the methods often used is the

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construction of three circles on a globe slate with each station as the center and a radius corresponding to the respective distance from the epicenter. The epicenter lies at the point of intersection of the circles. In practice however, certain errors always creep in, which may result in a triangle formed by joining the points of intersection of the circles whose centroid may nevertheless be assumed as the epicenter quite safely, (Duff, 1993). The exact location of earthquake epicenters requires detailed knowledge of the seismic velocities along the entire path, but especially under the source area and the receiving station. The main reason for the intersection triangle is, however, that the seismic rays travel to the seismograph from the focus and not from the epicenter, (William, 1997).

In this study, instead of constructing three circles, eighty four (84) three simultaneous equations in terms of epicentral distance, station coordinates and the coordinates of the epicenter formulated by combining standard empirical relations and simple geometry laws (Sogade, Yerima and Okon, 1994; Okon, 1999) were obtained from the number of station readings available using the principle of mathematical combination. The solutions of these equations only yielded 71 epicenters instead of 84. This means that 13 of the equations have no solutions indicating may be station readings used to formulate such equations did not belong to the same event even though they were recorded on the same day. The results show that the earthquakes recorded in the Ethiopian western plateau on this day originated from two main sources. One of the sources appears to be a fault plane curving from NW plane into the NE plane while the other is in the SW plane, which is likely to be an area source.

GEOLOGICAL HISTORY OF ETHIOPIA

About 920 million years ago, a period between the ends of Pre-Cambrian era and the Paleozoic, the crystalline rocks that formed the basement complex of the present Afro-Arabian swell had been above sea level for a long time. Such a long period of denudation and erosion left the earth's surface of East Africa, Ethiopia and Arabia almost as completely peneplained as the rest of the African continent.

About two hundred and twenty five million years ago, crustal motion started. During the late Triassic and early Mesozoic, a regional epirogenic sinking of the crust commenced causing a progressive transgression of the ocean from the southeast northwestward, that is from Indian ocean coast of present Somalia in the general direction of lake Tana in northeast Ethiopia. This downward crustal movement, concomitant with a sedimentation process, was active during the first half of the Mesozoic era. It came to a stop in the middle of the same era, reversed its direction into an upward motion during the upper Jurassic, brought the crust's surface up to sea level by the end of the Mesozoic, 65 million years ago, and finally uplifted through intermittent but progressive phases throughout Tertiary and Quaternary times to the present level of more than 3 km (Gouin, 1979) above sea level.

SEISMIC REGIONS OF ETHIOPIA

The events are grouped according to the regions that naturally emerged from the breakup of the African segment of the Nubian swell: two highland or plateau regions and the rift units that dissected them. Fig.4 diagrammatically identifies the selected regions as: Region A, the Ethiopian western plateau; Region B, the southern plateau; Region C, the main Ethiopian rift, Afar and the southern Red Sea; Region D, the Gulf of Aden western sector; and Region E, the Gemu-Gofa and Turkana rifts. The events that occurred in region A on 1 June 1961 were considered in study.

It should be noted that contrary to what one would expect, the plateau-rift escarpments, which are geologically structural parts of the rifts, have been included in regions A and B rather than C. This is because 90% of the seismic and volcanic activity is connected with the rifts; regions A and B would otherwise have almost no place in this work. On the other hand, however, the aim of grouping the events in this manner is the evaluation of the seismic hazards to life and property, and although most shocks originate along rift structures, the greatest damaging effects are found on the plateaus where the majority of the population resides and where most published investigations have been conducted. Therefore, the division of Ethiopia into seismic regions has been influenced by the location of the seismic effects on the society rather than strictly by geological norms.

THEORY AND METHOD

From fig.1, we assume that the coordinates of the epicenter be denoted by E (θ,ϕ) and that of the reporting station S (α,β).

Using simple geometry laws it can be easily deduced that for a spherical earth ;

$a = \sin\theta\cos\phi,\ b = \sin\theta\sin\phi,\ c = \cos\theta$ (1)

$d = \sin\theta,\quad e = -\cos\phi,$ (2)

$g = \cos\theta\cos\phi,\ h = \cos\theta\sin\phi,\ k = -\sin\theta,$ (3a)

$\tan\phi = b/a$ (3b)

where a, b, c *are the direction cosines* of the line joining the earth's center O to E: etc. and A, B, ...be corresponding constants for the station.

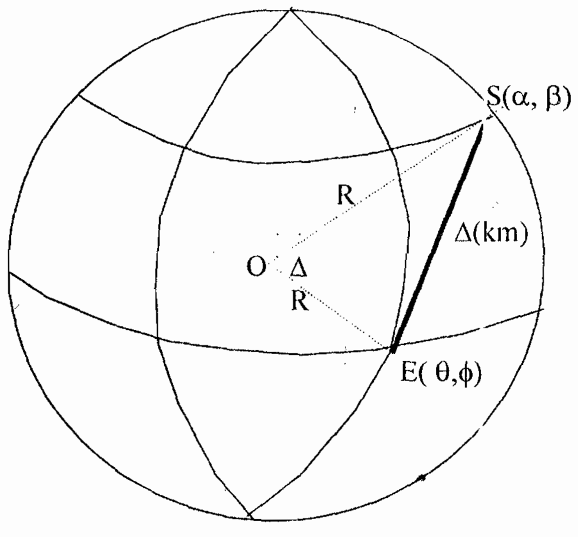

Fig.1 Positions of epicenter E, reporting station S and epicentral distance Δ on the earth's surface of radius R and center O.

The epicentral distance Δ is the distance between E and S measured as the arc-length ES in km or as the angle subtended by ES at the earth's center. Bullen et al (1985) deduced from (1), (2), and (3a) that

$$\cos\Delta = Aa + Bb + Cc \quad (4)$$

For three station readings of a particular event, equation (4) yields three simultaneous equations in a, b, and c, (Sogade, Yerima, Okon, 1994; Okon, 1999)

$$\cos\Delta_1 = A_1a + B_1b + C_1c \quad (5a)$$

$$\cos\Delta_2 = A_2a + B_2b + C_2c \quad (5b)$$

$$\cos\Delta_3 = A_3a + B_3b + C_3c \quad (5c)$$

The values of a, b, and c can be obtained by solving equation 5c, 5b, and 5c simultaneously and consequently the coordinates of the epicenter θ and ϕ by substituting these values of a, b, and c in equation (1) and (3b).

Using Gouin (1979) standard empirical relationships for 251 events, Yerima (2000) has shown that

$$\Delta = 237.74 + 23.77M \quad (6)$$

where M is the surface-wave magnitude

For n station readings of a particular event, taking 3 at a time to form three simultaneous equations, using the principle of mathematical combination the total number of such three simultaneous equations is given by

$$N = \frac{n!}{3!(n-3)!}\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

In this study, for any given M, equation (6) was used to calculate Δ and for n=9, equation (7) gives N=84.

RESULTS AND DISCUSSION

The plot of latitude versus longitude (fig.2) reveals that the sources of tremors recorded in the Ethiopian western plateau (A) on 1 June 1961 are mainly due to two sources. One of the sources is a fault plane curving in from the NW plane into the NE plane in form of a parabola cutting the vertical axis and the other in the SW plane in the form of area source with three as point source. In this study, the faulting from the NW plane passing into the NE plane corresponds to the cross-section of the Plateau Afar escarpment and upper margin at the latitude of Kara Kore, the region that was seismically active in May-August 1961, (Gouin, 1979).

Geographically, the area of observed maximum damage was situated along the Addis Ababa-Asmara highway between latitude 10^0 and 11^0 and longitude 39.7^0 and 39.9^0. At these latitudes, highway No.1 runs along the upper margin of the eastern escarpment of the Ethiopian western plateau, which is dissected longitudinally by the Borkenna and Robi marginal grabens and transversely by strong NE-SW faulting curving from Afar, Gouin (1979). In this study, the part of the fault plane in the NE plane and *the sources of the epicenters in the SW* Plane agree with the existence of the strong NE-SW faulting.

The villages of Majete (N10.27^0, E39.56^0) and Kara Kore town in Ethiopia were destroyed. In Robi a tabacco drying plant was destroyed and near Debre Berhan (N9.7^0, E 39.5^0) a power transformer was brought down from its supporting poles. Boulders were dislodged and rolled down from the slope of volcanoes Fantale (N9.0^0, E 39.9^0) and Boseti Guda (N8.5^0, E 39.5^0), (Gouin, 1979).

Table 1: List of station readings on tremor of 1 June 1961- courtesy of Gouin[5].

S/N	α	β	M	Δ(km)
1	10.60	39.30	8.3	435.0
2	10.40	39.90	7.8	423.1
3	10.53	40.17	7.8	423.1
4	10.00	39.50	6.7	397.0
5	10.60	39.80	6.3	387.5
6	09.00	39.00	6.5	392.2
7	10.63	39.81	6.4	389.9
8	10.30	39.90	6.5	392.2
9	10.48	39.87	6.5	392.2

Table 2: USCGS and JED epicenters.

S/N	JED		USCGS		S/N	JED		USCGS	
	θ	ϕ	θ	ϕ		θ	ϕ	θ	ϕ
1	10.84	39.82	10.70	39.90	18	10.40	39.84	9.88	40.00
2	10.71	39.90	10.60	39.90	19	10.31	39.98	9.49	39.96
3	10.69	40.00	10.60	39.80	20	10.25	40.08	9.50	39.80
4	10.64	40.04	10.50	39.90	21	10.24	40.18	9.39	40.20
5	10.62	40.10	10.50	39.70	22	10.15	40.15	9.39	40.00
6	10.58	40.20	10.41	39.84	23	10.16	40.05	9.29	40.01
7	10.62	39.85	10.39	39.99	24	9.85	40.04	9.00	40.20
8	10.58	40.00	10.39	39.90	25	9.80	39.98	9.00	39.99
9	10.52	40.10	10.39	39.81	26	9.81	39.91		
10	10.52	40.22	10.39	39.78	27	11.20	40.51		
11	10.48	40.10	10.39	39.60	28	10.54	40.81		
12	10.48	40.12	10.30	39.90	29	10.41	40.23		
13	10.45	39.92	10.28	39.80	30	10.37	40.22		
14	10.41	40.18	10.10	39.63	31	10.42	40.12		
15	10.40	40.25	10.10	39.59	32	10.42	40.10		
16	10.40	40.11	10.00	40.00	33	10.55	40.08		
17	10.40	40.00	10.00	39.96	34	10.57	40.10		

Fairhead et al (1970) used the group location technique developed by Douglas (1967) and coded JED (for Joint Epicenter Determination). The JED plot (fig.3) was obviously biased toward the east with respect to the center of observed maximum intensity. Such a bias in the absolute geographical location of a JED epicenter cluster can easily happen as its absolute location is dependent on the accuracy of a master or sub-master reference event and on the tectonic regional anomalies separating the reference event from the actual zone activity. In this case, the "restraint" reference is the epicenter of 18 April 1966, located in the Gulf of Aden, about 1000 km east of Kara Kore. On the other hand, the plot in fig. 4 illustrates the epicenter relocations 7 adopted in this study, and the big triangle represents the area containing (JED) 34 and USCGS (25) illustrated in fig. 3.

In this study (Table 3), positive values of θ means epicenter is located in the geographical north (N) and negative values indicate epicenter in the geographical south (S) while positive and negative values of ϕ respectively designate

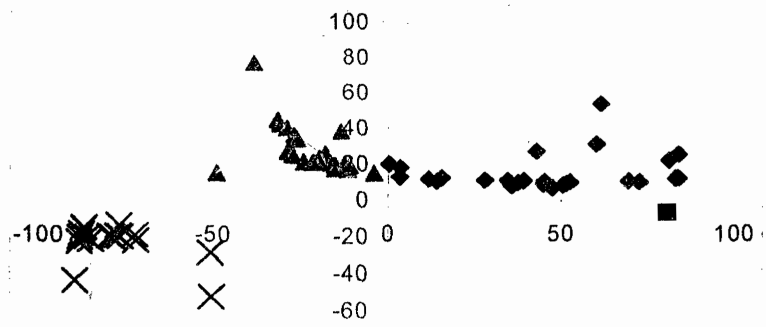

Figure 2: Epicenters located NE( ), NW( ) and SW( ) in the Ethiopian Western Plateau .

epicenter in the east (E) and west (W). In fig. 2, the mean values of 28 epicenters located in the NE plane, 25 in the NW plane, and 17 in the SW plane respectively are (N15.03^0, E 47.08^0), (N 27.24^o,W 22.30^0), and (S22.68^o, W78.45^0). There is only one epicenter located in the SE plane, which appear to originate from the faulting in the NW and NE planes. The 28 epicenters located in the NE plane were most likely responsible for the Kara Kore tremors in Ethiopia and they differ in both latitudes and longitudes from those of USCGS and JED. These differences in latitudes and longitudes may be attributed to the dependency of absolute location of JED epicenter on the accuracy of a master reference event and on the tectonic regional anomalies separating reference event from the actual zone activity.

CONCLUSIONS

This study has provided a simple method of

Table 3: Results of epicenters located in the Ethiopian western plateau.

S/N	N	0	ϕ	S/N	N	θ	ϕ	S/N	N	θ	ϕ
1	1, 2, 3	9.87	52.60	32	2, 3, 7	18.11	3.52	63	3, 7, 9	20.70	-21.70
2	1, 2, 4	8.14	35.82	33	2, 3, 8	-28.18	-50.69	64	3, 8, 9	26.98	42.96
3	1, 2, 5	25.40	83.85	34	2, 3, 9	37.93	-13.57	65	4, 5, 6	-	-
4	1, 2, 6	8.90	44.97	35	2, 4, 5	36.33	-26.99	66	4, 5, 7	-	-
5	1, 2, 7	21.93	81.15	36	2, 4, 6	16.56	-11.56	67	4, 5, 8	10.91	34.51
6	1, 2, 8	15.12	-49.05	37	2, 4, 7	34.05	-26.20	68	4, 5, 9	15.51	12.32
7	1, 2, 9	-43.19	-89.52	38	2, 4, 8	-52.09	-50.45	69	4, 6, 7	-	-
8	1, 3, 4	8.41	50.65	39	2, 4, 9	-	-	70	4, 6, 8	12.03	83.08
9	1, 3, 5	53.55	61.41	40	2, 5, 6	44.64	-31.73	71	4, 6, 9	-21.64	-72.08
10	1, 3, 6	9.04	51.56	41	2, 5, 7	76.99	-38.53	72	4, 7, 8	10.66	39.21
11	1, 3, 7	31.14	60.09	42	2, 5, 8	-	-	73	4, 7, 9	11.08	27.90
12	1, 3, 8	6.83	47.55	43	2, 5, 9	-	-	74	4, 8, 9	10.45	45.21
13	1, 3, 9	-6.59	80.60	44	2, 6, 7	42.11	-31.11	75	5, 6, 7	-	-
14	1, 4, 5	-19.86	-78.59	45	2, 6, 8	-	-	76	5, 6, 8	13.05	3.40
15	1, 4, 6	12.15	83.76	46	2, 6, 9	-	-	77	5, 6, 9	14.88	-4.09
16	1, 4, 7	-19.17	-79.51	47	2, 7, 8	-	-	78	5, 7, 8	26.80	-28.74
17	1, 4, 8	12.08	83.45	48	2, 7, 9	-	-	79	5, 7, 9	24.94	-27.44
18	1, 4, 9	-14.98	-87.18	49	2, 8, 9	-	-	80	5, 8, 9	20.68	-21.16
19	1, 5, 6	-19.50	-76.61	50	3, 4, 5	20.08	-12.46	81	6, 7, 8	9.67	37.53
20	1, 5, 7	-18.84	-72.39	51	3, 4, 6	10.73	14.10	82	6, 7, 9	10.63	69.39
21	1, 5, 8	-21.31	-84.93	52	3, 4, 7	19.03	-11.02	83	6, 8, 9	11.61	11.69
22	1, 5, 9	-22.32	-88.38	53	3, 4, 8	-	-	84	7, 8, 9	17.60	-15.27
23	1, 6, 7	-19.03	-77.31	54	3, 4, 9	25.83	-18.06				
24	1, 6, 8	12.10	83.49	55	3, 5, 6	20.36	-16.38				
25	1, 6, 9	-14.52	-87.07	56	3, 5, 7	21.24	-24.13				
26	1, 7, 8	-19.76	-86.08	57	3, 5, 8	20.88	-21.50				
27	1, 7, 9	-20.01	-88.10	58	3, 5, 9	20.89	-21.54				
28	1, 8, 9	-17.86	-87.77	59	3, 6, 7	19.58	-15.28				
29	2, 3, 4	-13.35	-76.99	60	3, 6, 8	39.85	-28.99				
30	2, 3, 5	19.88	0.35	61	3, 6, 9	23.20	-19.71				
31	2, 3, 6	10.01	72.58	62	3, 7, 8	20.62	-21.28				

W here N is the serial numbers in Table1 representing the values of α, β, and Δ used in generating equations.

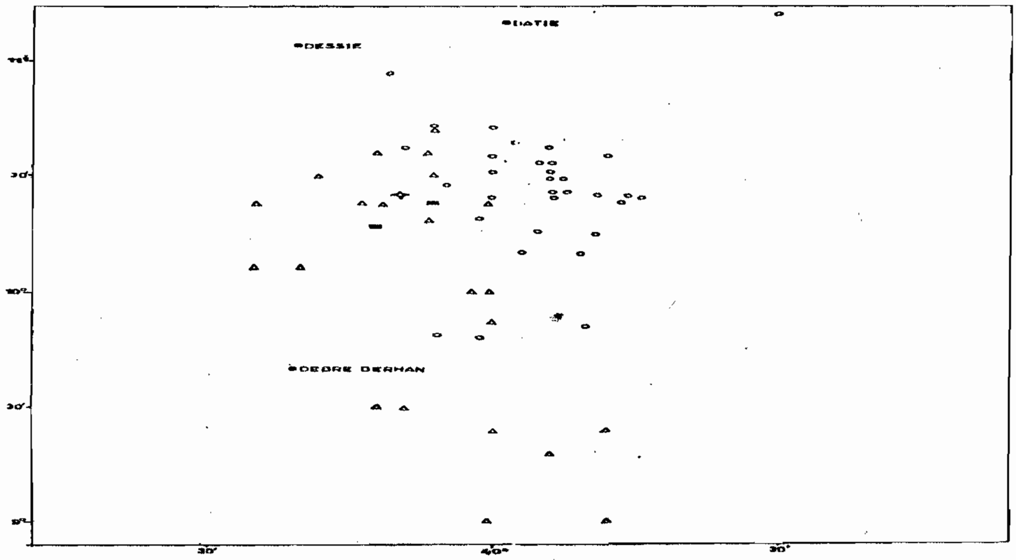

FIG.3 : LOCATION MAP OF THE USCGS(Δ) & JED(o) EPICENTRES

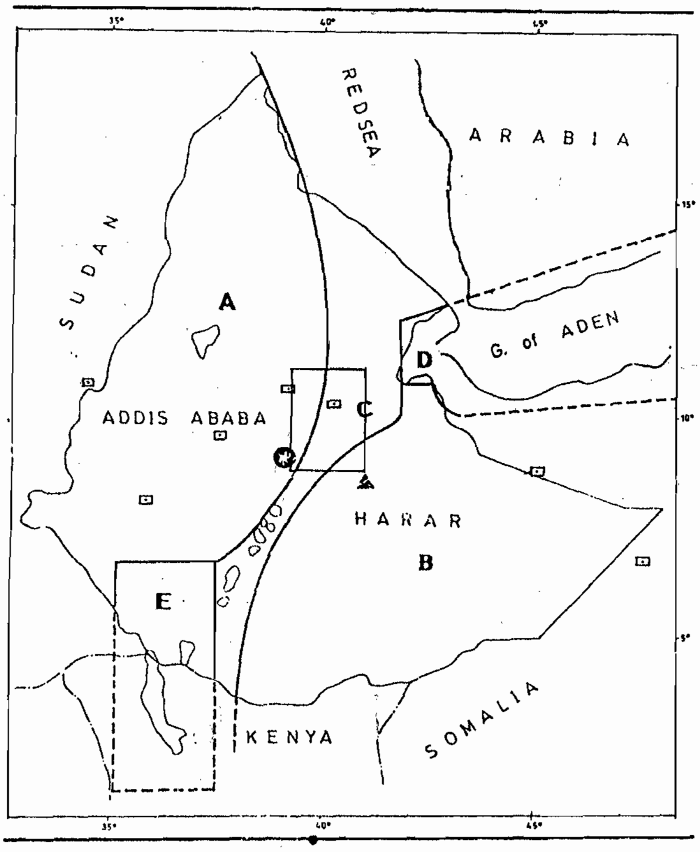

Fig. 4 Natural subdivision of Ethiopia and the Horn of Africa into five district structural units or seismic regions. A represents the Ethiopian Western Plateau, B the southern plateau, C the main Ethiopian rift Afar and the southern Red Sea, D the Gulf of Aden western sector, and E the Gemu-Gofa and the Turkana rifts. Area showing USCGS and JED epicenters (fig. 3) is here designated by ☐ Located epicenters- ⊡

determining earthquake sources in the Ethiopian western plateau, which gives reasonable results for comparative studies. There is room to improve on its accuracy, which was not covered by this work due to lack of globe slate to carry out construction.

Not all signals registered by stations on the same day are from the same source. This was shown when some station observations yielded to inconsistent equations that have infinite solutions. It may be that such readings were either wrongly observed or mistaken for signals from different sources that coincidentally arrived at the stations the same time. Based on the result of this study, it is recommended that such equations be disregarded.

If the epicentral distance can be accurately determined from the seismograph instead of calculating it from empirical formula, this method would provide the exact location of the epicenter since the station coordinates can always be precisely measured.

This method is cheaper and faster when we have station that can accurately record epicentral distance since it does not involve cost movement as in the case of macroscopic evaluation, and problems in construction technique are avoided.

This method revealed reality of different types of earthquake source-fault, point source and area source, and epicenter determination is dependent on the number and coordinates of stations.

Absolute location of epicenter does not require master reference event and tectonic regional anomalies separating reference event and actual zone activity can be avoided.

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