GEOPHYSICAL RESEARCH LETTERS, VOL. 9, NO. 8, PAGES 793-796, AUGUST 1982

RECONNAISSANCE MICROEARTHQUAKE SURVEY OF SULAWESI, INDONESIA

R. McCaffrey* and R. Sutardjo**

Earth Sciences Board, University of California, Santa Cruz, CA 95064

**Institute of Meteorology and Geophysics, Jakarta, Indonesia

Abstract. Several hundred earthquakes were recorded during the operation of a two-week five-station portable seismograph network on Sulawesi, Indonesia. Forty one of these events were locatable and half of these occurred beneath the eastern Gorontalo Basin in a north dipping zone which extends from the Batui Thrust on the East Arm of Sulawesi to about 100 km depth beneath the Gorontalo Basin. The Batui Thrust is the site of thrusting of the Banggai Islands continental fragment beneath the East Arm ophiolite and oceanic crust of the Gorontalo Basin. The observation of a zone of earthquakes dipping to the north from this thrust zone suggests that the leading edge of the Banggai Island block was subducted to at least 100 km depth. The eastern Gorontalo Basin earthquake zone may connect with a deep seismic zone beneath the Celebes Basin. Beneath the western Gorontalo Basin, a very narrow zone of earthquakes dips to the south, probably within lithosphere of the Celebes Basin subducted at the North Sulawesi Trench. Three shallow earthquakes occurred near Lake Matano in central Sulawesi, possibly on the Matano Fault, and their composite focal plane solution suggests east-west extension. The occurrence of only one earthquake on the Palu Fault and the lack of short S-P times at a station operated on the fault indicate that this feature was very quiet during the survey period.

Introduction

Eastern Indonesia represents one of the most seismically active and tectonically complex regions of the world. The detailed distribution of the abundant shallow earthquake activity has remained enigmatic, however, due to large distances between the regional seismograph stations in the area. During December of 1978, a temporary seismograph network was installed on Sulawesi as a cooperative program between the University of California (Santa Cruz), the Institute of Meterology and Geophysics (Indonesia) and the Geological Research and Development Centre (Bandung, Indonesia). The purpose of the survey was to obtain local arrival time data to help describe more accurately the distribution of earthquakes in Sulawesi and to test potential sites for future permanent seismograph stations in eastern Indonesia. Prior to operation of stations in Sulawesi, a network was operated around the Molucca Sea and the results of that are presented by McCaffrey (1982).

*Present address: Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139

Paper number 2L0976.
0094-8276/82/002L-0976$3.00

Tectonics of Sulawesi

The geology of Sulawesi reveals four main belts: a westernmost volcanic belt (lower Miocene to Quaternary) which includes the North Arm, a central schist belt, an east-central ultramafic and ophiolite belt and the easternmost continental fragments, the largest of which is the Banggai Islands block (Fig. 1). In general, the Sulawesi rocks suggest a late Cenozoic, east facing trench-island arc system which collided with the Banggai Islands continental fragment resulting in uplift of the Sulawesi ophiolite and slowing or cessation of subduction. The site of the present suture between the Sulawesi ophiolite and the Banggai Islands block is the Batui Thrust (Silver, 1981).

Central Sulawesi is bisected by the active, left-lateral Palu and Matano Faults (Fig. 1). Several large earthquakes have been centered on or near these faults in the past 80 years (Fig. 1) (Duda, 1965; Bath and Duda, 1979) but very few are routinely located on these faults by the ISC. The Palu Fault connects with the North Sulawesi Trench in the southern Celebes Basin. Earthquake hypocenters deepen to the south away from the North Sulawesi Trench (Hamilton, 1974; Cardwell et al., 1980) but appear to be confined to the western half of the Gorontalo Basin even though the North Sulawesi Trench extends eastward almost to the northern tip of the North Arm. Beneath the eastern Gorontalo Basin, intense earthquake activity is observed within the contorted southern edge of the Molucca Sea plate subducted to the west beneath the Sangihe Arc (Fig. 1).

The Field Study

From December 12 to 26 portable seismographs were deployed at Palu, Toli-toli, Gorontalo, Luwuk and Makale (Fig. 1, Table 1). Short-period vertical seismometers were used at all stations. Arrival time data were also obtained from permanent stations at Makassar (MKS), Manado (MNI), Ambon (AAI), Balikpapan (BKB), and other Indonesian and Philippine stations (see Hodgson, 1980).

Earthquakes recorded during the local survey were located by a single event least-squares locations scheme (Bolt, 1960) after station delays were calculated by the method of joint hypocenter determination (Dewey, 1971) utilizing fifteen of the most widely recorded events. Earthquakes were relocated twenty times while adding random errors of 1.0s standard deviation to all arrival times and the resulting standard errors in latitude, longitude, depth and origin time were used to

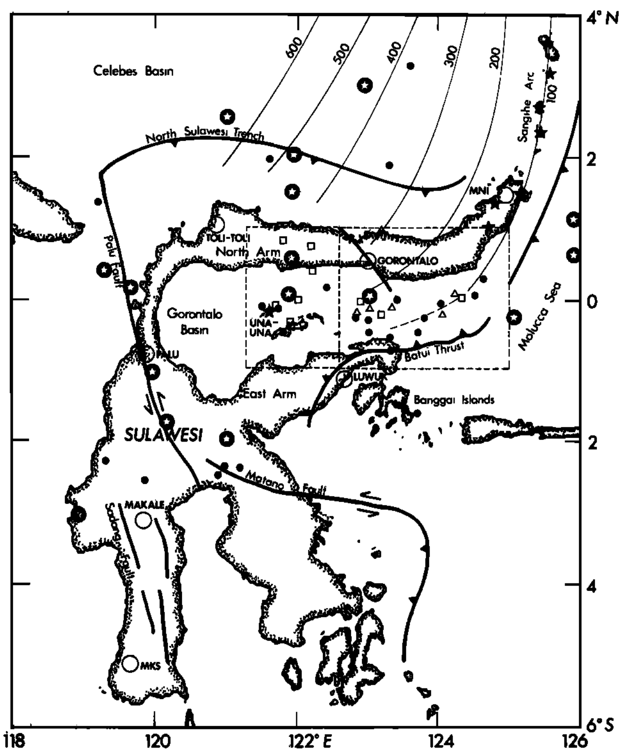

Fig. 1. Tectonic map of Sulawesi modified from Hamilton (1979) and Silver (1981). Thrust faults are shown with barbs on upper plate. Solid stars represent active volcanoes and open stars in black circles show locations of large shallow earthquakes that have occurred in the past 80 years (Duda, 1965; Bath and Duda, 1979). Large open circles are locations of permanent and temporary seismograph stations. Small symbols represent earthquakes recorded during the survey and depth ranges are as follows: 0-60 km - solid circles; 61-100 km - triangles; and 100-200 km - squares. The dashed boxes enclose the area of the projection in Fig. 2 and are separated by a dashed line at 122.6°E into areas referred to in the text as the east and west Gorontalo Basin. The thin solid lines in the northeast are contours (in kilometers) to the top of the subducted Molucca Sea lithosphere and are taken from Cardwell et al. (1980). Finally, the thrust fault shown to the east of the Sangihe Arc is that of the collision complex over-riding the island arc slope rather than the Molucca Sea plate thrusting under the arc. See Silver and Moore (1978) for more information. 1° equals approximately 111 km in latitude and longitude.

judge the stability of each location. Herrin et al., (1968) travel times were used for P arrivals and S times were taken from the table of Jeffreys and Bullen (1958). More discussion of the methods can be found in McCaffrey (1982).

Results of the Earthquake Survey

Half of the earthquakes located occurred in a narrow east-west trending zone at shallow and intermediate depths beneath the eastern half of the Gorontalo Basin (Fig. 1). In cross-section these earthquakes define a northward dipping zone which apparently shallows toward the East Arm of

Table 1

Temporary Seismograph Station Data

Station	Latitude	Longitude	Operation Dates
Luwuk	0° 56'S	122° 47'E	Dec. 10-26
Palu	0° 49'S	119° 53'E	Dec. 14-24
Makale	3° 06'S	119° 51'E	Dec. 13-25
Toli-toli	1° 03'N	120° 50'E	Dec. 12-26
Gorontalo	0° 33'N	123° 03'E	Dec. 12-26

Sulawesi from a depth of about 100 km beneath the center of the Gorontalo Basin (solid dots in Fig. 2). The top of the seismic zone appears to dip away from the East Arm at about 25° and becomes vertical at depths greater than 60 km. In general, the distribution of earthquakes from the local survey is similar to ISC locations (Cardwell et al., 1980) with the significant exception of the appearance of shallowing towards the East Arm.

The seismic zone projects towards the East Arm to the Batui Thrust (Figs. 1 and 2). The Batui Thrust has been observed on the East Arm and offshore in reflection profiles (Silver, 1981) as the site of underthrusting of the Banggai Islands continental block beneath the East Arm ophiolite and southern Gorontalo Basin crust, respectively. The obvious inference is then made that the slab dipping to the north beneath the Gorontalo Basin was once the leading edge of the Banggai Islands complex which was subducted to a depth of at

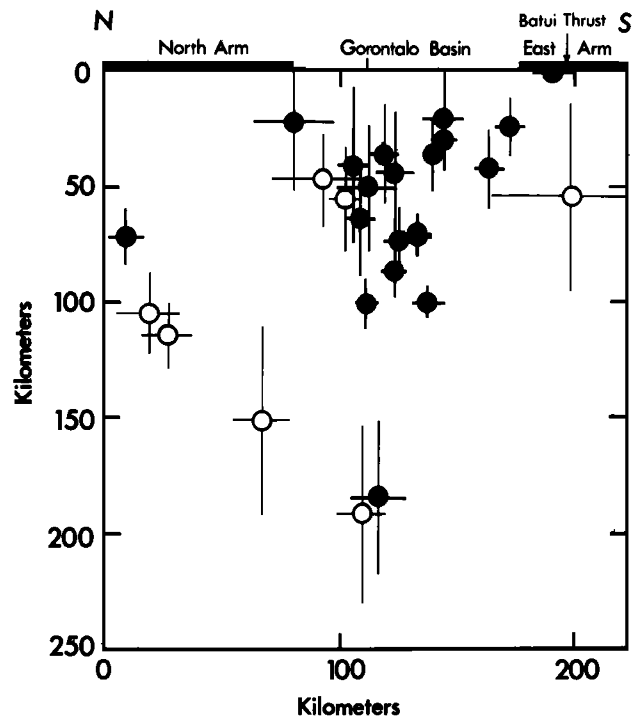

Fig. 2. Projection of earthquakes from the Gorontalo Basin onto a north-south striking vertical plane. The area of the projection is shown in Fig. 1. Closed symbols are events which occurred west of 122.6°E. The error bars shown for each event are the standard deviations in depth and latitude calculated by adding random errors to the arrival times at each station during twenty location computations.

least 100 km beneath the East Arm and Gorontalo Basin.

The distribution of the ISC earthquake locations suggests continuity between the west dipping seismic zone from the Molucca Sea and the intermediate zone beneath the eastern Gorontalo Basin (Fig. 1) (Cardwell et al., 1980; McCaffrey, 1982). If this is true and if the earthquakes recorded locally occur within a single slab then a physical connection between the Molucca Sea plate and the Banggai Islands block is suggested. The Batui Thrust may be the southern extension of the now buried trench which existed east of the Sangihe volcanic arc prior to collision with Halmahera in the Molucca Sea (Silver and Moore, 1978).

West of 122.6°E, in the western Gorontalo Basin, only a few earthquakes were detected during the local survey although this area was in the center of the seismograph array (Fig. 1). In cross-section (Fig. 2 - open circles), hypocenters appear to align in a southward dipping zone consistent with previous findings from ISC and USCGS data (Cardwell et al., 1980; Hamilton, 1974, respectively). Earthquakes in this zone are generally felt to occur within lithosphere of the Celebes Basin subducted at the North Sulawesi Trench. The deepest event recorded in the western Gorontalo Basin was at about 200 km depth with an epicenter about 50 km northeast of the volcano, Una-una (Fig. 1).

In Figure 2, two events from the eastern Gorontalo Basin appear to be part of the south dipping zone. These events are located close to the dashed line in Figure 1 separating the two areas and are therefore probably part of the south dipping zone beneath the west Gorontalo Basin. Similarly, two of the three shallow events from the west Gorontalo Basin occurred near this boundary and could be grouped with those of the east Gorontalo Basin.

Five shallow earthquakes were recorded from central Sulawesi (Fig. 1). None of these were near the Palu Fault but three were located in the region of Lake Matano (Figs. 1 and 3) and may have occurred on the Matano Fault. Composite P-wave first motion data for the three shallow earthquakes which occurred near Lake Matano (Fig. 3) are not consistent with left-lateral strike-slip along the Matano Fault and suggest, instead, north striking normal faulting. It has been suggested (E.A. Silver, personal communication, 1978) that Lake Matano is

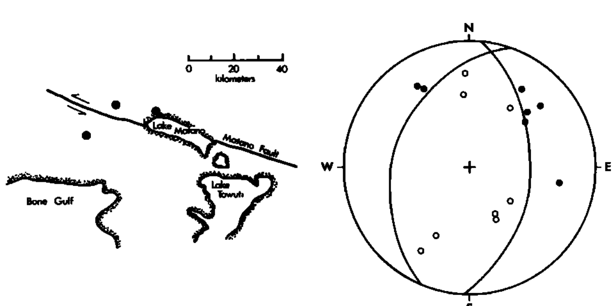

Fig. 3. Composite focal plane solution for the three shallow earthquakes which occurred near Lake Matano. Open circles represent dilational and solid circles compressional first motions. The map at the left shows the locations of the events (solid dots) relative to the Matano Fault.

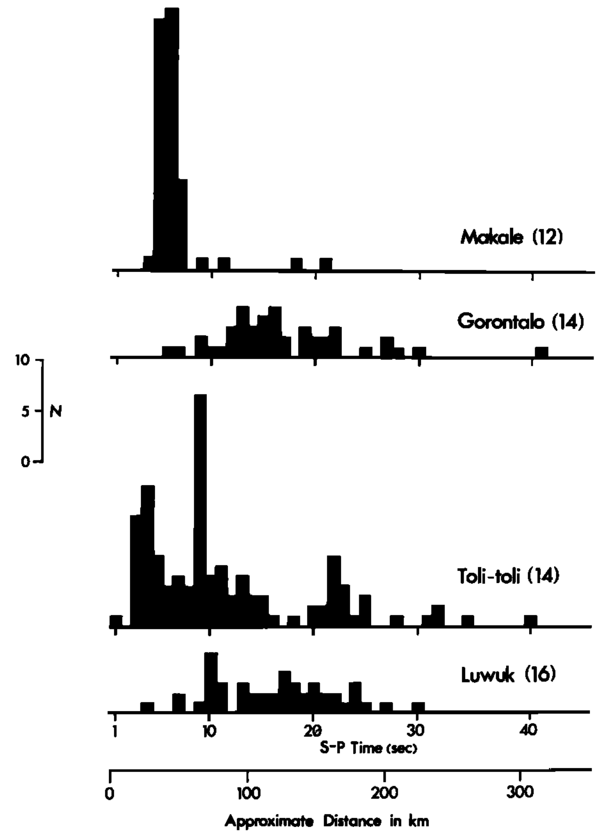

Fig. 4. Histograms of the number of earthquakes (N) with the given S-P interval recorded at each station. The number in parentheses is the number of days the station operated. The distance scale is calculated with V_p=6.5 km/s and V_s=3.5 km/s for a surface focus.

a pull-apart basin between the east and west limbs of the Matano Fault. The focal mechanism presented here supports such east-west extension near the lake since the size of the probable errors in the epicentral locations of these events do not preclude their true location from being beneath Lake Matano. Two earthquakes were located in west-central Sulawesi (Fig. 1) where association with tectonic features is unclear. One earthquake was found on the northern extension of the Palu Fault and two along the North Sulawesi Trench but coverage of these regions by the array was not good enough for accurate locations.

S-P Times

By examining the frequency of occurrence of the differences between the P and S arrival times at a single station, some valuable insights may be gained regarding the seismicity of a region which may not be apparent in the distribution of earthquake foci. This is especially valuable if stations are widely spaced and many events are recorded at too few stations to permit a unique location. Histograms of S-P times plotted against frequency of occurrence for each of the temporary stations are shown in Figure 4.

The station at Palu is not represented in Fig. 4 since very few clear S-P times were readable and there were not recognizable local earthquakes (S-P times less than 15 s) recorded. The lack of local events in the Palu area again suggests that the Palu Fault generates very little routine activity. The Palu Fault is reminiscent of sections of the San Andreas Fault along which there is little microseismic activity observed over long periods of time (Allen et al., 1965).

Earthquakes recorded at Gorontalo and Luwuk displayed a range of S-P times from 5 to 30 s. The scarcity of S-P times less than 10 s at Gorontalo indicates that no earthquakes occurred on the Gorontalo Fault (Katili, 1978). The earthquakes producing the peak at the S-P interval of 10 s at Luwuk were too close to be coming from the central Gorontalo Basin but could have been beneath the East Arm region or the area just north of the East Arm at 122°E where extensive shallow activity is evident in ISC locations (Cardwell et al., 1980).

The distributions of S-P intervals at Toli-toli shows three distinct peaks at 4, 9 and 22 s. The peak at 22 s may be associated with activity in Gorontalo Basin whereas those at 4 and 9 s cannot. The peak at 9 s (corresponding to a distance of approximately 70 km) may be related to activity in the region west of Toli-toli in which many events are found in ISC locations. The sharpness of the 9 s peak and the striking similarity of the recorded signal characters at Toli-toli among these events suggest that they probably originated within a small volume of the earth. The peak at 4 s is broader, ranging from 3 to 5 s of S-P time. These events occurred within approximately 25-40 km (including depth) of Toli-toli, a region within which only one shallow event has been located by the ISC. The source of this activity is enigmatic since no active tectonic features are known in the Toli-toli area.

The station at Makale recorded a large number of local earthquakes with S-P intervals ranging from 5 to 7 s. These events probably originated in the seismically active region 30 to 50 km north of Makale (Hamilton, 1974). This zone lies approximately half-way between the Palu and Sadang Faults and is not simply interpreted.

Summary

A local earthquake survey in Sulawesi of eastern Indonesia has allowed a closer look at the seismicity of this active area than has previously been possible. Most of the activity observed was generated beneath the eastern Gorontalo Basin. A southward shallowing trend for these events suggests that they are related to the Sulawesi-Banggai Islands collision and may occur within a subducted portion of the Banggai Islands block. Conversely, a southward dipping zone was observed beneath the west-central Gorontalo Basin, probably within lithosphere of the Celebes Basin subducted at the North Sulawesi Trench.

Central Sulawesi displayed little activity except for a few events near the Matano Fault in the vicinity of Lake Matano and in west-central Sulawesi. The Palu Fault appeared to be very quiet whereas the Makale and Toli-toli areas are characterized by many small events.

Acknowledgements

The field work was supported by the Government of Indonesia, H.O. Wood Foundation of Carnegie Institution, the Geological Society of America and Sigma Xi. R.M. was supported by NSF grants OCE76-020365, EAR77-10034, and OCE78-08693. We acknowledge the assistance of Suciono, Dr Satuju, E. Sukamto, R. Buyung, R. Susanto, E.A. Silver, Y.S. Joyodiwiryo, J. Widartoyo and H.M.S. Hartono. Graphics by D. Hall. We thank R.K. Cardwell and one anonymous reviewer for valuable comments.

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(Received April 20, 1982;
revised June 1, 1982;
accepted June 15, 1982.)