34. CORRELATIONS OF TEPHRAS IN CELEBES AND SULU SEA BASINS: CONSTRAINTS ON GEODYNAMICS[1]

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ABSTRACT

Tephra ash fall and pyroclastic flows in the Celebes and Sulu seas provide a good record of the explosive volcanic activity of the neighboring volcanic arcs. Distribution of volcanic ash layers vs. time is compared to the average distribution in the Philippine Sea and tentatively correlated with the volcanic sequences known on the surrounding landmasses. During early Tertiary (Eocene and Oligocene), the Celebes Basin recorded mostly the activity of the large volcanic arc that could be the Philippine or more likely the Sunda arc.

Paradoxically, the west Philippine Basin shows a decrease of the ash component during the early Oligocene. After the almost complete cessation of volcanic activity in the Philippine arc, no volcanic activity is noticeable until the latest Miocene except pyroclastic flows on the flank of the Cagayan Ridge and the Sulu Basin. Therefore volcanic series known in the Philippines and on Sabah during early Miocene (21–17 Ma) and middle Miocene (15–11 Ma) may not have produced explosive volcanism. However, the pyroclastic flows of the Sulu Sea did not generate ash-fall deposits within the sediments of the Celebes Sea. The first pyroclastic event is coeval with the early middle Miocene tectonic event of Panay and Mindoro that brought the Cagayan arc against the Palawan block. The second pyroclastic event, at 10 Ma, corresponds to the second collision phase of the Philippine arc with the Eurasian margin. It is recorded in both the central Philippine Basin and Sulu Basin–but not in the Celebes Basin–and fits well the activity of the older Sulu arc. No volcanic activity is registered until 7.5 Ma, when a new subduction, probably the Sangihe arc, began with the geochemical signature of an immature island arc. Early Pliocene tephras record a basaltic series that could correspond to the proximal volcanic ridges of northern Zamboanga, followed by a relative absence of discrete tephra. The Pleistocene renewal of volcanic activity from two different magmatic series are compatible with the incipient volcanism along the Cotabato Trench (immature island arc geochemistry), and with the basaltic plateaus of the central cordillera of Mindanao. This new geodynamic framework is consistent with new subduction along the Philippine Trench around 4 Ma as suggested by the tephra of the west Philippine Basin.

INTRODUCTION

The Celebes and the Sulu seas (Fig. 1) are fringed with volcanic arcs ranging in age from middle Eocene to Quaternary (Hamilton, 1979; Mitchell, 1986). One of these, the Sulu arc, lies along the boundary between the Celebes and the Sulu basins and extends onto Mindanao on the Zamboanga Peninsula. Other arcs are the north Sulawesi, bordering the Celebes Sea on the south, the Sangihe, between the Celebes Basin and the Molucca Sea, the nascent Cotabato, the Cagayan, separating the inner and outer Sulu Basins, the Negros-west Luzon, and the Philippine, on the present boundary between the Eurasian margin and the western edge of the Philippine Sea Plate. In addition, large volcanic centers that have not been related to any active subduction exist in central Mindanao.

The ash layers are tephra-fall deposits ranging in thickness from 2 mm to 15 cm; they also contain detrital clay or silt when slightly reworked by bioturbation. The tephra-fall deposits record explosive volcanism in volcanic landmasses that surround the basins. Pyroclastic deposits, which are also discussed in this paper, depend on regional volcanism (Klein, 1985). On the other hand, ash deposition is very dependant on atmospheric circulation patterns, tectonically controlled volcanism (Kennett et al., 1977; Karig, 1983), and proximity to island and seamount sources. In the Lesser Antilles arc, over 80% of the volcanics produced were deposited in the adjacent seas, but the distribution and the relative proportion of ash fall and pyroclastics is dependent on the morphology of the arc slope and on the wind direction in the troposphere (Sigurdsson et al., 1980). In addition, basaltic magmas are rarely represented as ash deposits. Therefore, effusive volcanic series dated on land are not necessarily present as ash layers within contemporaneous sediments, and volcanic activity likely will be detected by the presence of detrital-weathering smectite. Once the source is known, dating of the sediments can provide reliable ages for the beginning of volcanic arc activity that is often difficult to date on land.

PRESENT AND PALEOWIND SYSTEMS

The ash particles, mainly glass shards, pumice, and crystals, sometimes mixed with lithic fragments, are carried by prevailing winds, including the upper atmosphere wind currents.

The present wind pattern (Times Atlas of the World, 1977) indicates that, during winter, the Philippine arcs (Philippine arc, Negros arc, Cotabato arc, Luzon arc), and to a minor extent the arcs of the central and eastern Philippine Plate, could act as sources for the ash layers of both Celebes and Sulu basins. South of the present Equator, north-directed winds could transport ash particles from the Sunda arc (Figs. 3 and 4) up to the Celebes Basin.

During July, most of the air masses move northward and would disperse ash from the western and southwestern Ring of Fire in the Philippine Sea. Kinematic and paleomagnetic

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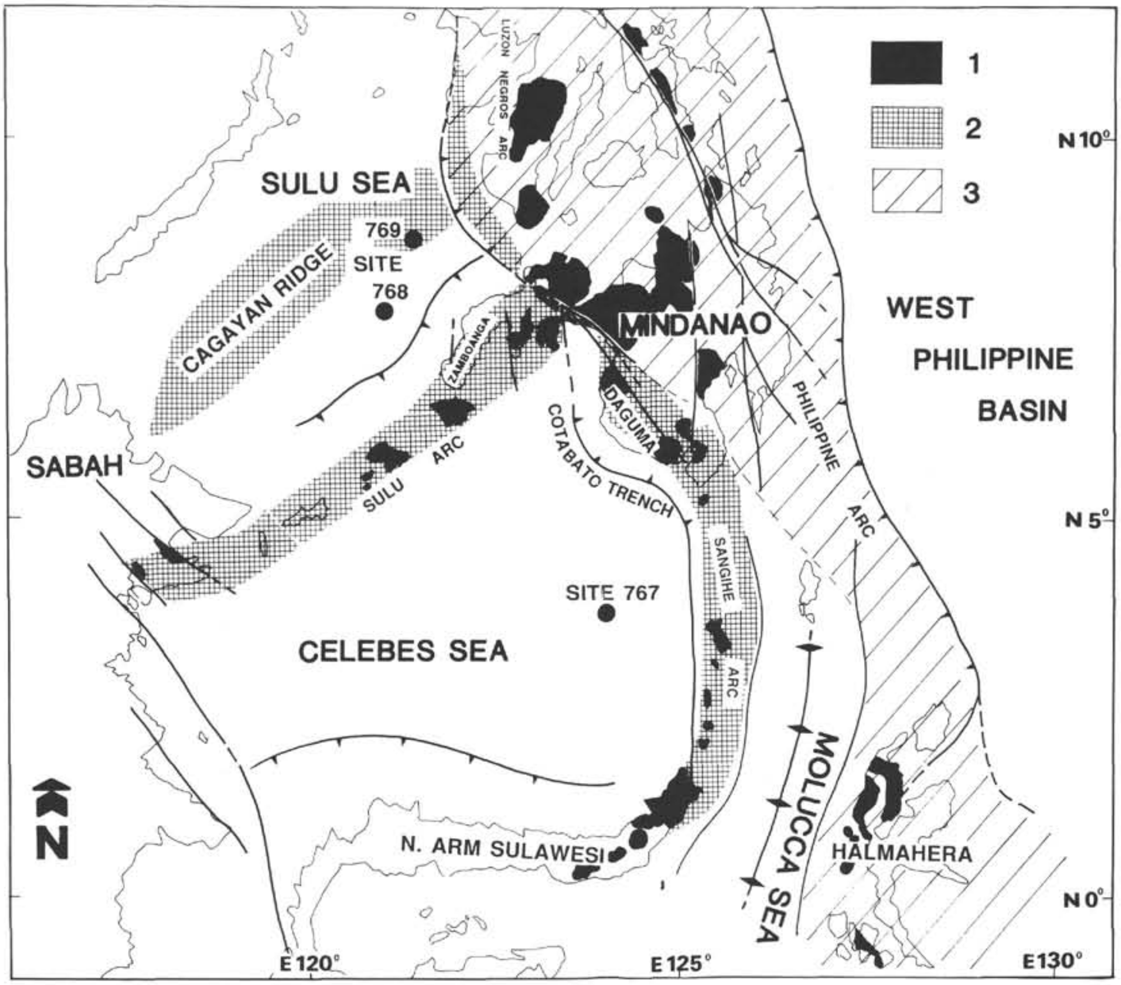

Figure 1. Sketch map showing the dominant volcanic belts, arcs, and basins. 1: Pliocene-Quaternary ages, 2: Neogene, and 3: Paleogene-latest Oligocene (Philippine arc).

data reveal that the Philippine Sea Plate has rotated clockwise since early Cenozoic time by about 40° (Karig, 1975; Louden, 1977; Klein and Kobayashi, 1980; Ranken et al., 1984), inducing subduction of its northern side along the Nankai Trench and oblique collision with the eastern margin of Eurasia since early Neogene time (Jolivet et al., 1989). During the same period, Australia has been moving northward relative to Eurasia, inducing closure of the marginal basins of Eurasia (Rangin and Pubellier, 1990). Thus, we assume that no continent or major mountain belt on the Pacific side could drastically change the wind pattern during the late Tertiary.

METHODOLOGY AND RELIABILITY OF DATA

We plotted all the discrete ash layers (disregarding scarce dispersed ash in hemipelagic or pelagic sediments) vs. time, taking into account core recovery. We calculated the recovery within each time interval according to the method developed by Cadet and Fujioka (1980) and Cadet et al. (1990) (Fig. 2). Ash layers are dated using biostratigraphic (scale of Berggren, 1985) or magnetostratigraphic markers, and ages are extrapolated between markers according to the sedimentation rates. The chosen time unit is 0.5 Ma except for the basal part of the sections, for which it is 1 Ma. Petrographic and geochemical study of the most representative samples of each peak of ash layer frequency allowed us to correlate between sites. We did electro-probe microanalyzer and atomic emission spectrometer as well as X-ray fluorescence studies. Detailed discussion of these analyses is given by Pouclet et al. and Desprairies et al. (both, this volume).

Aside from the tephra-fall deposits, which often are altered when older than Pliocene, we considered extensive pyroclastic flows of the Sulu Sea Basin sites (see below). Likewise, reworked ash materials near the bottom part of the section in the Celebes Basin were included, as they indicate possible contemporaneous volcanic activity on land and the large amount of clastic turbidites of late early Miocene. Nevertheless, due to the high grade of alteration of the lower part of the sections, few reliable data can be extracted from the Celebes Basin prior to late Oligocene.

CELEBES SEA

Three major peaks in ash-layer frequency are present at Site 767 of Leg 124 (Fig. 2) in the northern Celebes Sea. Spot coring in Site 770 did not allow any correlation.

The most recent peak is Pleistocene to Holocene in age (younger than 2.5 Ma) and is composed of numerous vitric white-to-light-gray ash layers present above 200 mbsf. In some layers, glass content is up to 95% and shows a rhyolitic to dacitic composition with medium to high K_2O and Na_2O content. These tephras are produced by large-magnitude explosive eruptions (plinian to ultraplinian) (Walker, 1973) as

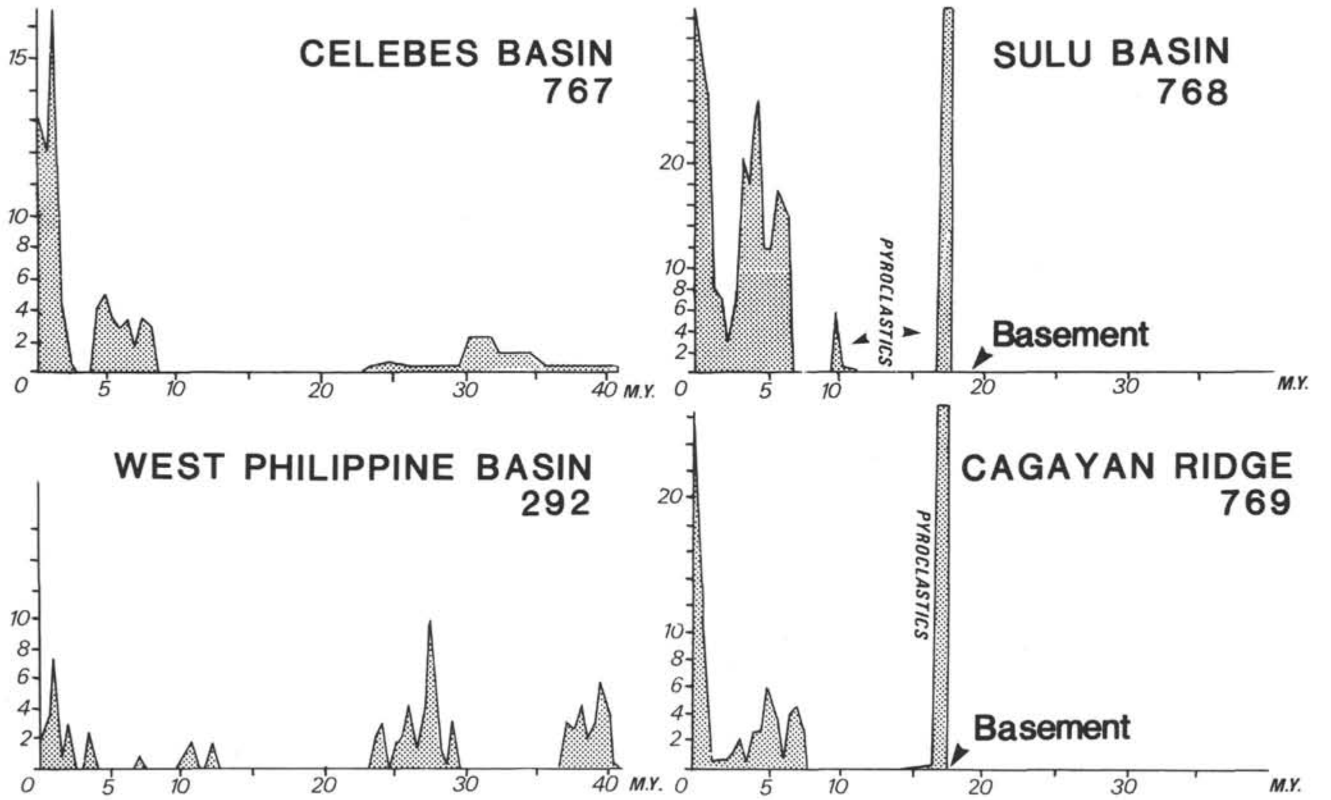

Figure 2. Ash layers and volcaniclastic gravity flows frequency vs. 0.5 Ma time-interval histogram. From data compiled at DSDP Site 292 and ODP Sites 767, 768, and 769.

described by Sigurdsson et al. (1985) in the Lesser Antilles. These tephras, with high alumina-moderate alkali content, which may correspond to a high alumina basalt series (Pouclet et al., this volume).

Explosive volcanic activity seems to vanish between 2.5 and 4 Ma. A change in the nature of the alteration products of volcano-derived materials also coincides with the beginning of this period around 4 Ma (Desprairies et al., this volume).

The late Miocene to early Pliocene (410–250 mbsf and approximately 8–4 Ma) is a period of intermittent ash deposition. A large part of the glass is altered into phillipsite and Al-beidellite (Desprairies et al., this volume), but the rest displays andesitic composition (Pouclet et al., this volume). Glass shards are present, together with abundant lithic fragments, plagioclase, hornblende and pyroxene. The type of fractionation and the low Al and alkalies contents characterize the moderately potassic andesitic series of an immature island arc (Pouclet et al., this volume). This composition may indicate a renewal of volcanic activity of the Sangihe (and Negros) trenches, at least by early Pliocene time (Figs. 1 and 4).

During early and middle Miocene, (mostly between 400 and 650 mbsf) no discrete ash layer is recognizable and the lithostratigraphic column is dominated by detrital grains including thick turbidites in which the volcaniclastic fraction, if present, is represented by silt-sized plagioclase. The paucity of ashy material (Fig. 2) within the hemipelagic claystone is also difficult to interpret. It could be either a gap in the volcanic activity, a period of more effusive volcanism, or a dilution by the turbidites. Clay component analyses (Rangin, Silver, von Breymann et al., 1990) show a general decrease in the weight-percent smectite, down to 10%, that fits with the increase of the terrigenous fraction marked by the transition from massive claystone to silty claystone. This curve is disrupted by sharp peaks with values as high as 80%. This could be interpreted as a general dilution of the smectite that remained high between occurrences of turbidites. Alternatively, the presence of sharp intervals of volcanic-derived material polluting a low-smectite sedimentary background cannot be excluded.

From the Mid-Eocene to early Miocene (below 700 mbsf), a few diffuse ash beds are present, scattered in reddish pelagic claystone. In this interval, the frequency diagram must be interpreted with caution. This low-amplitude peak corresponds in fact to a few occurrences of ash layers between Cores 124-767C-76X and -9R in Hole 767C, but due to sedimentation rate and compaction, they are distributed over a wide span of time. Although the ash layers are reworked, the morphology of glass reflects more-or-less contemporaneous volcanic activity onshore with a maximum at the Oligocene-Miocene boundary. Fresh glass is present that shows rhyolitic composition and whose morphology reflects explosive volcanism. In addition to glass, volcanic components include crystals and lithics. However, secondary minerals indicate *in-situ* alteration of glass that could have been more abundant originally. In this portion of the section, smectite content is paradoxically rather low compared to the portions where no discrete ash is observed. This possibly indicates that the smectite comes directly from the alteration of glass *in situ*. In such a case, all of the lower part of the section in the Celebes Basin would have remained in an environment influenced by volcanogenic input.

SULU SEA

Ash distribution in the Sulu Sea is fairly homogenous throughout the lithostratigraphic columns of Sites 768 and 769, located in the southeast Sulu Basin and on the southeastern

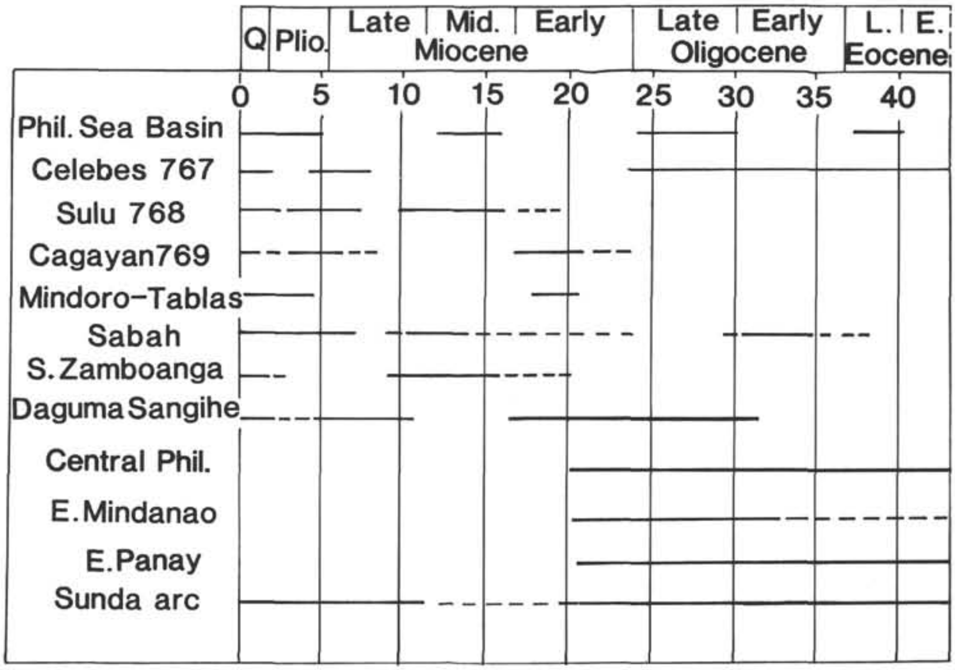

Figure 3. Correlation of the volcanic sequences in landmasses surrounding basins, with the tephra-fall deposits in the sediments of Sulu and Celebes basins.

flank of the Cagayan Ridge, respectively (Fig. 1). Spot coring at Site 771 did not allow correlation. Diagrams (Fig. 2) show a long period of activity from the end of Tortonian (7 Ma) to Present in which two peaks can be distinguished.

The most recent peak is during the Pleistocene to Present and shows rhyolitic to andesitic compositions, mostly represented by abundant glass and frequent crystals in both Sites 768 and 769 (Rangin, Silver, von Breymann, et al., 1990). Analyses of glass and minerals show moderate potassic andesitic series of an immature island arc at least in the middle to late Pleistocene strata of Site 769 (see Pouclet et al., this volume). The source of these tephras is difficult to establish because many volcanic arcs are active during this period of time, including the Sangihe arc, the Cotabato arc, the central Mindanao volcanic chain, the Sulu arc, and the Pleistocene and Holocene west Philippine arc (Figs. 1, 3, and 4).

The end of the Pliocene is marked by a decrease in the frequency of ash layers at both sites of the Sulu Sea, accompanied by a significant increase in the crystal fraction of the volcaniclastic deposits (Rangin, Silver, von Breymann et al., 1990). Nevertheless, a probable high-alumina basalt series origin is detected in late Pliocene-early Pleistocene tephras. On land, close to the southeastern coast of the Sulu Sea, post-upper Pliocene basaltic flows (undated) compose the large northwest-southeast Aurora Ridge in northern Zamboanga and have been lately affected by extensional and wrench-faulting tectonics.

The second peak in volcanic activity is centered around 4 Ma and is characterized by the absence of glass, or a very weak proportion of the glassy fraction, relative to both crystal and lithic fractions. However, the increase of the clayey fraction may also be due to the alteration of glass.

Late early Miocene (17 Ma) to middle upper Miocene (7 Ma) is a time of relative quiescence of explosive volcanic activity, as the sedimentation is dominated largely by hemipelagic claystone. Although no ash layer is recorded on top of the Cagayan Plateau (Site 771) nor on the flank of the Cagayan Ridge (Site 769) during this period, several thick fining-upward sequences of tuff have been drilled in the Sulu Basin (Site 768) that document a short period of activity between 12 and 9.5 Ma. These deposits are definitely reworked together with plant debris and detritals but contain very fresh angular glass that attest to nearly contemporaneous eruptions of a mature arc with high-K andesites series (Pouclet et al. this volume). Considering the data on the Cagayan Ridge that indicate cessation of arc activity by early middle Miocene (Fig. 3), and because these tuffs were emplaced by gravity flows, the source may be located on the southern side of the basin, on the Sulu arc.

Late early Miocene strata are dominated by the emplacement of gravity flows of coarse and fine vitric tuff and lapillistones (Fig. 2). This part of the section is 197 m thick at Site 768 (Fig. 2) and is composed of mudstone and fine tuff with turbidite-like graded bedding and laminar flows of volcaniclastic materials, bearing partially devitrified glass shards and pumice. Hence we arbitrarily gave a maximum value to the ash frequency to saturate the diagram and keep its consistency. At Site 769 (Figs. 1 and 3) and Site 771, on the Cagayan Ridge, submarine and subaerial hyaloclastites of coarse tuff containing generally altered glass in addition to pyroxene and plagioclase have been found. Fresher material revealed a basaltic to andesitic composition with a signature of immature arc (Pouclet et al., this volume). At the base of the southeast Sulu Basin (Site 768), pyroclastites share similar characteristics (immature to intermediate) although rhyolitic compositions are also found. Basement underlying the hyaloclastites was not drilled. However, seismostratigraphic and petrographic observations allow us to correlate the volcaniclastic deposits in both Cagayan Ridge and Sulu Basin, where they overlay and post-date the basement together with a few meters of pelagic sediments. These sediments, although they contain minor amounts of glass and volcanic minerals, do not show well on the graphs (Fig. 2) because of the imprecisions of biostratigraphic data. These observations therefore suggest that the Cagayan arc was at least still active after the spreading had begun.

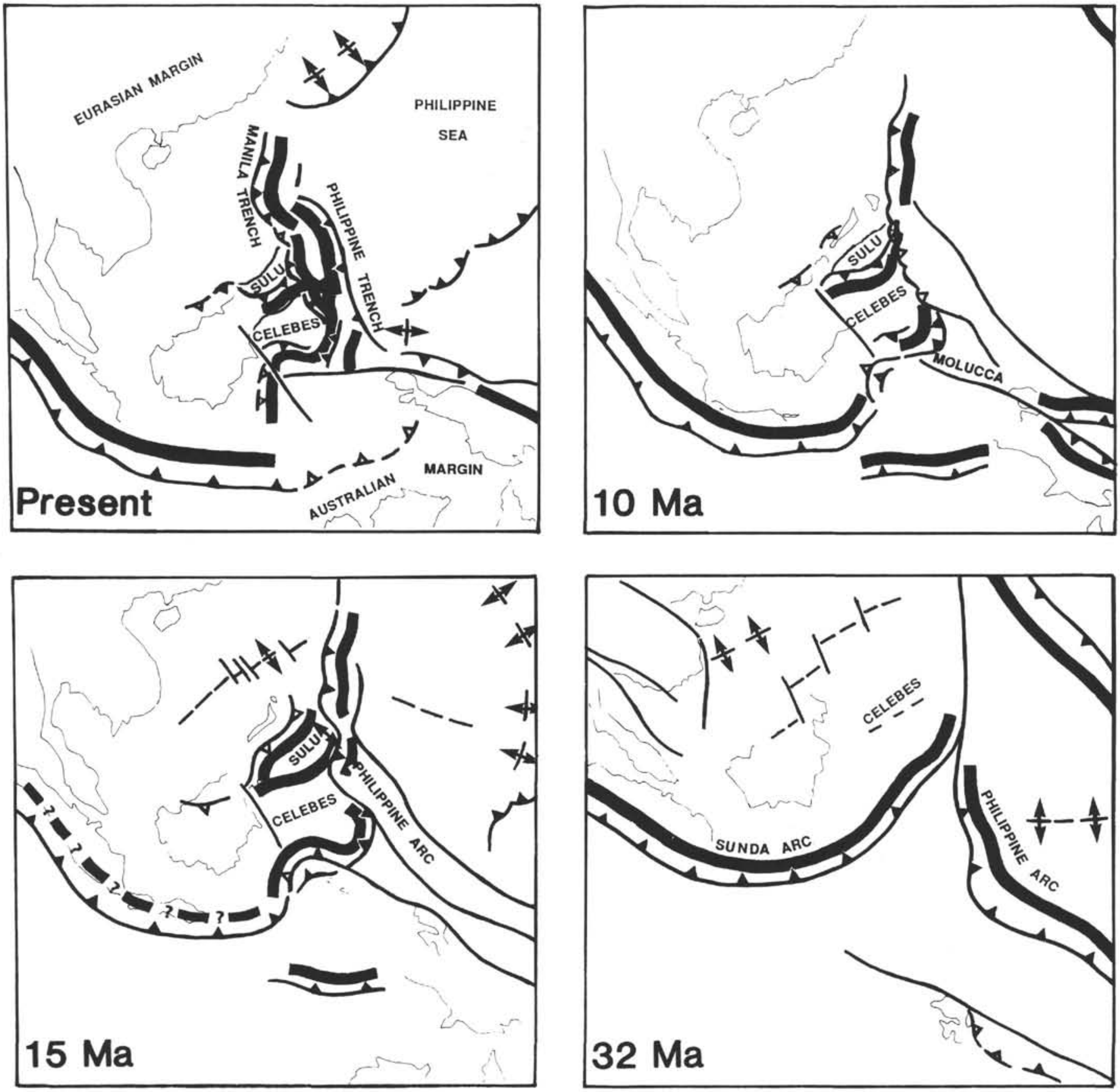

Figure 4. Location of the major volcanic arcs at 32 Ma, 15 Ma, 10 Ma, and Present. Kinematic maps are modified and simplified from the computed reconstructions of the western Pacific (Rangin, Jolivet, et al., in press). Thick lines represent extension of volcanic arcs, dashed when no isotopic dating exits. Barbed lines represent subduction zones.

CORRELATIONS AND DISCUSSION

Frequency of ash beds and dispersed ash in hemipelagic and abyssal deposits reflects the influence of the explosive arc volcanism surrounding the basins.

The Eocene-Oligocene volcanic activity recorded in the sediments of the Celebes Basin is coeval with the volcanic event dated around Zones NP23–24 (Rangin, Bellon, et al., 1990) in Sabah (Fig. 1). Its tectonic setting remains unclear, but it may be related to the subduction of a proto South China Sea (Holloway 1982, Taylor and Hayes, 1983) (Fig. 4). Another interpretation is to consider that these ash layers originated from the large volcanic arcs fringing the southern margin of Eurasia or the western margin of the Philippine Sea Plate. However, kinematic and paleomagnetic data from DSDP Site 292 (Karig, 1975; Louden, 1977; Klein and Kobayashi, 1980, Ranken et al., 1984) indicate a northward motion, of about 30°, of the Philippine Sea Plate carrying the volcanic arc extending from Halmahera to Mindanao and Luzon (Philippine Mobile Belt). This arc was therefore farther south during the Eocene (Fig. 4). The peak between 37 and 40 Ma observed in the Philippine Sea Basin probably shows the beginning of the activity of the arc, as Site 292 appeared to move away from the source with time. Comparison with the distribution of ash layers at Site 292 shows that the 32-Ma peak does not exist in the west Philippine Basin, supporting this hypothesis. The other source for the ashy sediments of the Celebes Sea is the Sunda volcanic arc, which may have extended through Sulawesi, where late Eocene volcanism was dated during summer 1990 (C. Rangin, pers. comm., 1990) and was the result of the subduction of the Indian Ocean beneath the Eurasian margin. Thus the peak in volcanic activity observed around 32 Ma could correspond to the proximity of both arcs by early Miocene time, when the Philippine arc reached the vicinity of the Celebes Sea.

The presence of ash layers around 25 Ma in the Celebes Sea fits very well with a maximum in the Philippine Sea Basin (Fig. 2) that corresponds to the activity of the Palau Kyushu-Bonin arc prior to splitting. If this is correct, the source of these tephra is located even further from the Celebes Sea. On the contrary, the relatively small volcanic arcs of Sulu, Cagayan, and the North Sulawesi arm do not appear at all in either the Celebes Basin or in the Philippine Sea Basin as discrete ash. The coeval activity recorded in the west Philippine Basin during Middle and early late Miocene seems therefore to be more related to subduction of the Pacific behind which the Shikoku Basin opened. Thus, it seems that we can only detect, in remote marginal basins, large and durable volcanic arcs.

Early Miocene pyroclastic flows of Sites 768, 769, and 771 have a source near the Sulu Sea. The correlation between the pyroclastic flows of the Sulu Basin, which post-date at least this part of the oceanic basement, and the hyaloclastites of the Cagayan Ridge suggests that the Cagayan ridge hyaloclastites do not belong to the arc that generated the back-arc basin. Furthermore, we cannot forget that if no volcanism exists below the Cagayan Ridge hyaloclastites before 17 Ma, the Cagayan arc is not the remnant arc for this part of the Sulu Sea back-arc basin. Volcanic series that include tuffs are known in the Philippines (Panay Island) and Sabah during Burdigalian time (20–16 Ma, Rangin and Pubellier, 1990), and are not recorded within the sediments of the Celebes and Sulu basins. We have to consider the possibility that volcanic activity was present on the Cagayan-Sulu arc prior to the opening of the basin, slowed down during the deposition of the brown clays around 17 Ma, and finally appeared again as pyroclastic flows (still in the nannofossil Zone NN5). On the other hand, the Sulu Sea pyroclastics could have originated in the Sulu arc southward (although they leave no trace within the sediments of the Celebes Basin). These pyroclastics would correspond to an early subduction of the newly born Sulu Basin. In any case they faded at around 15 Ma, at the time when collision occurred in Mindoro and Panay (Rangin, 1989). This middle Miocene period corresponds in both basins to a gap in tephra-fall deposits that accompanied an increase in continentally derived sediments (Rangin, Silver, von Breymann et al., 1990). It is related to a period of active erosion in the Philippines.

Late Miocene volcanic tuff reworked as turbidites was deposited around 10 Ma. It is found only in the Sulu Basin at a time when the illite/smectite content is the highest in the clay fraction and the detrital input is maximum in both basins. These volcanics range from dacite to evolved rhyolite. If the tuffs came preferentially from the Sulu Archipelago, then the Celebes Basin was protected from these volcaniclastic turbidites by a trench or ridge, possibly the tilted blocks offshore southern Zamboanga (Hinz and Block, 1990). In Zamboanga, east of the Sibuguey Gulf, the upper part of the Lumbog formation of middle Miocene contains pyroclastic flows (Gotas Member) which are not dated (Antonio, 1972). All along the Zamboanga Peninsula, thick volcanic series of andesites and volcaniclastics postdate Zone NN5 calcareous sediments and are covered uncomformably by the Lumbog formation.

This time of deposition is consistent with the ages obtained in northeastern Kalimantan (BRGM, 1982) in northeastern Sabah, where isotopic K/Ar ages between 13 and 10 Ma were found (Rangin, Jolivet, et al., in press, Fig. 3), and the Antique Range of Panay where highly deformed volcanics in the collision front bear nannofossils of Zone NN9 (Rangin et al., 1989). Therefore this second pyroclastic episode also appears just prior to the collision of the Philippine arc with the Eurasian margin, which occurred 10 Ma ago. This episode is contemporaneous with a peak in the west Philippine Basin, between 12.5 and 10 Ma.

In both Celebes and Sulu basins, volcanic activity is intense between 0 Ma and 7 Ma (late Miocene to present) and is coeval with the beginning of subduction in Sulu and Negros trenches (Mitchell et al., 1986) but also to the Sangihe arc and the Luzon arc (Wolfe, 1981). In the northern arm of Sulawesi, volcanic activity is recorded from 7 to 4 Ma and is still active in the northeast. This period exhibits two peaks well separated by an apparent lack of volcanic ash-fall deposits in the Celebes Basin (between 2.5 and 4 Ma), as well as a significant decrease in the Sulu Sea (1.5 and 3.5 Ma on the Cagayan Ridge; 2 and 3.5 Ma in the Sulu Basin). In addition, these age groups differ slightly in petrological composition. The discrepancy in these ages (8 Ma in the Celebes Basin, 7.5 and 6.5 Ma on Cagayan Ridge and in Sulu Basin) is less than the deviation of errors and cannot be considered significant.

The latest Miocene to earliest Pliocene volcanism corresponds on land to a compressive event marked by an unconformity or cessation of sedimentation in the basins that developed within the Philippine arc (Pubellier and Rangin 1989, Rangin and Pubellier, 1990, Aurelio et al., 1990). Also, transpressional features formed along the suture between the Philippine arc and the Eurasian margin along the Cotabato Basin (Pubellier et al., 1990). The collision between the Philippine arc and the Eurasian continental fragments led to the reversal of the subduction into the present Philippine Trench. It also generated the new Negros, Sulu, and Cotabato subduction zones. This event corresponded to a maximum in the ash-layer frequency but, due to lack of reliable ages on the late Tertiary volcanic centers south of Luzon, it is difficult to assign a specific source to the tephras found in the basins. The maximum observed can be divided into two peaks, of which only the older one (between 7 and 5 Ma) appears in the Philippine Sea Basin. It is characterized by medium K rhyolites, dacites, and abundant andesites from an immature arc (Pouclet et al, this volume). All the volcanic centers in Negros, Sulu, and east Philippines seem too young to have generated these tephras. Only the Sangihe arc, whose remnant slab extends northward beneath Mindanao Island, could be the source. It would vanish around 5 Ma when the Philippine arc docked with the Eurasian margin at the Miocene/Pliocene boundary.

The most recent peak, younger than 2.5 Ma, is prominent in both Sulu and Celebes Basins, as well as in the west Philippine Basin and the Japan Sea (Leg 127). It represents a well-documented change in the geodynamic evolution of the western Pacific that is dominated by the beginning of collision in Taiwan (Barrier, 1986) and in the Molucca Sea (Moore and Silver, 1982). However, its amplitude only reflects the very good preservation of the tephras. The older part of this peak in the Sulu Sea (lower to middle Pleistocene) clearly shows andesites, dacites, and rhyolites with high K (and low Al) contents, reflecting the existence of an immature arc (Pouclet et al., this volume). This could be related to either incipient subduction along the Cotabato Trench, which is responsible for the large volcanoes of North and South Daguma Range (Fig. 1), or to the reactivation of subduction along the Sulu Trench. This time interval is also filled by numerous radiometric ages in Luzon (Wolfe, 1981).

In the same time interval, Celebes Sea sediments recorded tephras produced by plinian to ultraplinian explosive volcanism with high alumina basalt series. They seem compatible with the tremendous amount of the central cordillera basaltic plateau of Mindanao that revealed radiometric ages between 0.25 and 1.15 Ma and are located along major north-south strike-slip fault zones (Pubellier et al., 1990). Volcanoes of central Mindanao include the Apo Mountain and are among the sources nearest to the Celebes Sea drilling sites. This interpretation is supported by the absence of such geochemical characters within the tephra of Sulu sediments.

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