cone was torn apart. Both structures - the tension phenomena of the Soropati cone and the compression structure in its eastern foot - disappear southward under the younger volcanic products of the Telemojo and Merbabu. However, it is clear that the Pajung-Rong ridge is a limited slice or wedge of volcanic products pushed away from the Soro-pati eruption centre in an ENE direction

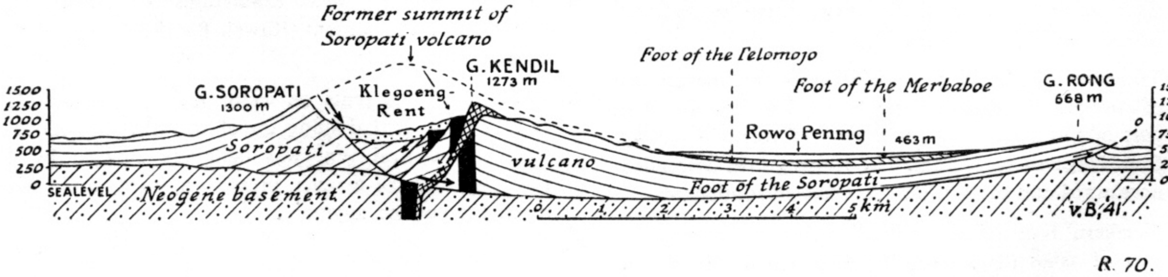

FIG. 276. *Section across the Soropati Complex.* (From VAN BEMMELEN, 1943, fig. 19)

Prior to the formation of the Klegung rent the Soropati volcano probably had a height of nearly 2000 m above sea-level. On its western side there was the Progo Valley depression and on its eastern side to Solo Valley depression. Both depressions were partly covered by the young pleistocene Notopuro breccias.

This Soropati volcano formed a load of more than a thousand million tons of volcanic rocks on a rather plastic foundation of marine neogene sediments (chiefly clays and marls).

The strains caused by this load radiated outward to the lower regions East and West of it.

The Solo Valley depression was at that time somewhat lower and closer to the Soropati cone than the Progo Valley depression. The load of the growing Soropati volcano finally became too heavy and the volcano collapsed; it was torn apart along the Klegung rent and its eastern portion slid away in the direction of the Solo depression. The Notopuro breccias at its eastern foot were pushed eastward, thus forming the overthrust wedge of the Pajung-Rong ridge and damming up the water of the Rowo-Pening marsh near Ambarawa.

Afterwards, during the Holocene, the magma rising through the vent of the Soropati built up a new cone, the Telemojo, which roofed the southern part of the Klegung rent. The composition of these younger magmatic products differs from that of the older period; the original magma of the Soropati was olivine basaltic, whereas more acid differentiates (augite-hypersthene-hornblende andesites) were erupted by the Telemojo.

The simultaneous formation of the Klegung rent on the one side, and the Pajung-Rong ridge on the other, represents the complementary effects of gravitational tectogenesis. The first resulted from the sideward sliding of the eastern portion of the Soropati cone, and the second was its complementary effect, viz. the compression and overthrusting of its eastern foot at a lower level.

Because of the fact that the southern part of the Kledung rent as well as that of the Pajung-Rong ridge are buried by the younger volcanic products of the Telemojo and the Merbabu, the southward extension of this structure is not known. To the East of the highroad, between Salatiga and Ampel, gently warped Notopuro breccias rise as flat islands from the smooth young-volcanic foot of the Merbabu. These post-Notopuro folds reach even beyond Karanggede, as far as 25-30 km from the summits of Soropati and Merbabu, and their axes are strongly convex to the East.

To these post-Notopuro folds belongs also the **Onto dome**, Southwest of Simo, at a distance of 25 km from the Merbabu summit. In the core of this dome "Black Clays" of the lower-pleistocene Putjangan layers are exposed, as well as some poly-mict gravels which are tentatively ascribed to the middle-pleistocene Kabuh Layers. Vertebrate fossils do occur in them, but these exposures are not yet as thoroughly investigated as those of the Sangiran dome, 20 km farther West. From the top of the Onto dome olivine basaltic lava issued after its doming up.[4])

These domelike warping and folding movements in the Notopuro breccias East of the Soropati and Merbabu cones might also be ascribed to superficial gliding movements of these breccias over the underlying plastic marls of the Kendeng ridge and the black clays of the Solo Zone, due to gravitational collapses of the Soropati and the older Merbabu.

A distance of 25-30 km of these secondary tectogenetic foldings from the summits of the collapsing volcanoes is not excessively large.

The secondary tectogenetic effects caused by the collapse of the Old Lawu reached as far as 45 km into the foreland (see hereafter).

In the Pajong-Rong ridge the whole compression was concentrated in a single overthrust at only 10 km from the Soropati; whereas farther southward the compression spread over an area between 10 and 30 km from the summit, and gave rise to four or five gentle folds in the area of Karanggede.

[4] See for the stratigraphy of this Onto dome under the heading of the Kendeng Zone and section IV of fig. 269 on pl. **28**.

It is interesting to note that the collapse of the Old-Merapi (in recent time) caused spreading in a westward direction, whereas the collapse of the Soropati (and that of the hypothetical basement of the Merbabu) at the beginning of the Holocene was directed eastward. These gravitational movements followed the line of least resistance which varies from place to place and in the course of time. The collapse structure of the oldest Merbabu is, buried under the present Merbabu cone with its radial sector-graben. However, the rift in the Merbabu basement-structure is still indicated by the NNW-SSE series of subrecent parasitic eruptions across the Merbabu cone (Kopeng and Kadjor lava flows, see map of the Merbabu, fig. 274).

The **Lawu Complex.** The volcanic complex of the Lawu between Surakarta and Madiun must be discussed more in detail, as it shows clearly the general structure of the Solo Zone; moreover, Sangiran and Trinil, the famous finding places of fossil Man, are situated at its North foot.

First the stratigraphy of the Ngawi Subzone between the Lawu and the Kendeng ridge will be discussed; then a description of the Lawu Complex in the Solo Zone *(sensu stricto)* will be given; finally, attention will be paid to the relation between the structure of this volcano and the folds in the Ngawi Subzone.

Stratigraphy of the Ngawi Subzone. (According to VAN Es, 1931, VON KOENIGSWALD, 1940, and VAN BEMMELEN, Geol. Survey Report Oct. 1937; see also map and sections II-VI of the Surakarta area, fig. 268 on pi. 34 and 269 on pi. 28).

A good exposure of the strata underlying this subzone, is found in the **Sangiran dome,** North of Surakarta, which has been cut by the antecedent Tjemoro River (sections III and V of fig. 269 on pi. 28).

The series begins with bluish gray marine clays and argillaceous sands with marine fossils (e.g. *Turritella bantamensis)* which belong to the Upper Pliocene. They can be correlated with the Sonde marls of the South flank of the Kendeng, near Trinil. The marine facies terminates with a horizon of *Balanus-Mmtsionc.* Upon this horizon follows a stratum with fresh water molluscs, called *Corbicula-bed* by VAN ES, which forms the base of some dozens of metres of coarse breccias (augite-hornblende andesites) with marine as well as freshwater molluscs. These breccias contain lumps and fragments of the *Turritella-* and *Corbicula-beds.*

These breccias are perhaps the result of large landslides from older volcanic structures in the Solo Zone, viz. the young-miocene "Banjak" volcanoes; it may be also possible that some fresh volcanic material was erupted at the end of the Pliocene, causing great lahars. On the North flank of the Lawu, in the Camping anticline which will be described presently, limestones comparable with the Klitik limestones of the Kendeng Zone, are overlapping similar augite-hornblende andesite breccias.

These Klitik limestones are as old as the Sonde marls exposed in the Sangiran dome, and therefore, it appears more probable that these lower breccias of Sangiran on top of the marine strata are landslides from these older volcanic complexes (called Banjak volcanoes).

After the formation of the lower breccias of Sangiran the western part of the Ngawi Subzone formed a fresh water lake in which about 200 m of Black Clays were deposited. This lake was the result of the ponding up of the drainage system by lahars of the oldest Wilis volcano in the East, while the Kendeng Zone to the North emerged already as a low threshold separating it from the sea-strait formed by the Randublatung Zone. In the latter zone marine sedimentation continued (Blue Clays).

An intercalation in the Black Clays of Sangiran of a yellow marine clay horizon of only 0.5 m thickness proves an invasion of the sea of short duration.

Moreover, these Black Clays contain some dia-tomaceous beds which have an estuarine facies according to REINHOLD (1937, p. 66).

In the Black Clays many vertebrate fossils of the Djetis fauna were found, so that they belong to the lower-pleistocene Putjangan Layers.

The facies suddenly changes after the quiet circumstances of sedimentation during the formation of the Black Clays. On top of them a series of cross bedded, fluviatile sandstones and gravels was deposited.

The latter begin with a calcified, polymict conglomerate. The volcanic constituents consist of waterworn detritus of older formations, and do not represent contemporaneous volcanic activity.

These conglomerates and sandstones are a typical synorogenic formation, consisting of denudation products from the Kendeng Zone in the North (Globigerina-limestone, etc.), as well as detritus from the rising geanticline of Java to the South (cataclastic quartz, volcanic material), being deposited in the interjacent strip of the Ngawi Sub-zone in which relative subsidence continued.

These beds are rich in vertebrate fossils of the Trinil fauna with *Pithecanthropus*, and belong to the middle-pleistocene Kabuh Layers.

The Kabuh Beds of Sangiran are covered by a series of volcanic breccias and tuff sandstones which are called Notopuro breccias. The volcanic breccias of the Bapang section (fig. 277) belong to the basal horizon of this formation and are found here pseudo-conformably on the Kabuh Beds. 5 m below this breccia horizon VON KOENIGSWALD found amongst other fossils a *Duboisia*-mandible (donated to the Raffles Museum in Singapore) in a calcified conglomerate also containing some cal-cedony components.

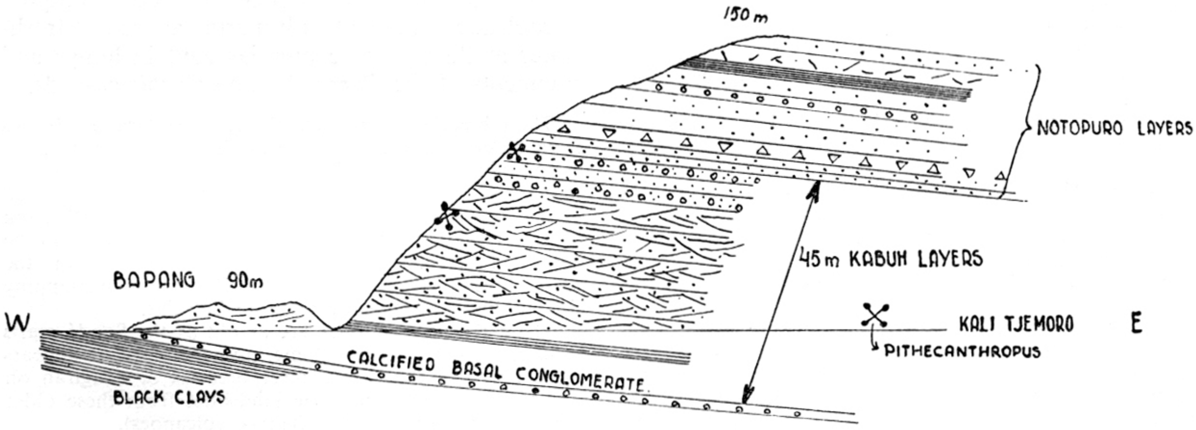

FIG. 277. *Section of the East flank of the Sangiran dome near Bapang.*

It is not certain whether the 10 m of sandstones and conglomerates between the Notopuro breccias and the cross-bedded sandstones of the Kabuh Beds should be assigned to the former or to the latter. In exposures between Sangiran and Surakarta the Notopuro breccias He with a sharp unconformity upon the Kabuh Beds. They begin with a coarse basal conglomerate, which contains components of calcedony and milky quartz besides andesitic boulders. (See fig. 278).

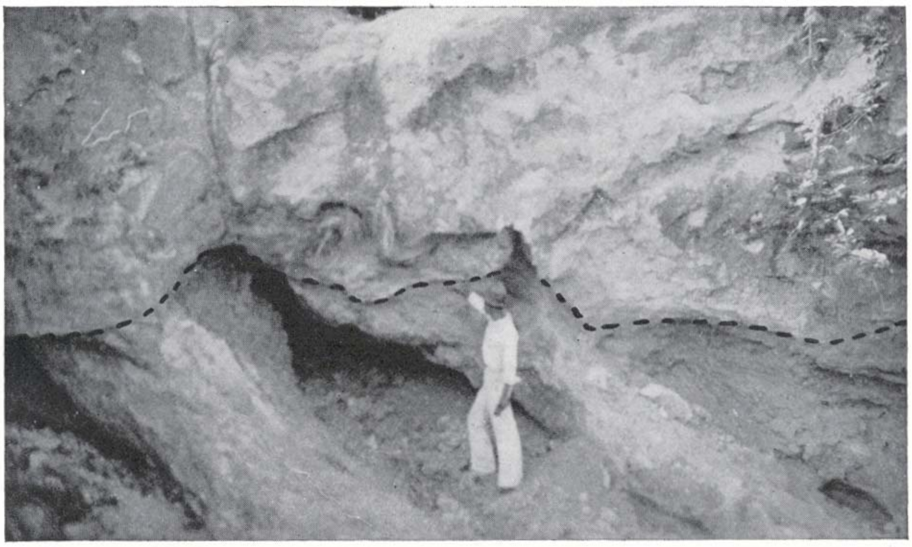

FIG. 278, opposite to p. 569. *Unconformable position of Notopuro conglomerates and breccias on the Kabuh Layers.* (West of the bridge of the main road across the Waturiver, 2.5 km North of Surakarta); Photo VAN BEMMELEN.

The age of the Notopuro Beds

It is possible that the conglomerate layer in the Bapang section with the *Duboisia-mandible* belongs already to the basal conglomerates of the Notopuro formation. In fig. 277 (Bapang section) this layer is assigned to the Kabuh Beds, but VON KOENIGSWALD (1940, p. 39), is inclined to consider it as the basal layers of the Notopuro Beds, dating the latter as Middle Pleistocene on account of this *Duboisia* find. However, the vertebrate remains in this horizon are all very badly preserved and might occur on secondary sites, being derived from the underlying Kabuh Beds. Therefore, if these strata really represent the basal conglomerates of the Notopuro Layers, the Trinil fossils do not yet prove the Trinil age of the latter. Farther North, in the Baringinan anticline near the village Tanon, conglomerates at the base of the Notopuro breccias, which overlap black clays of the Putjangan stage, contain typical Trinil fossils *{Axis* cf. *lydekkeri, Duboisia kroeseni, Stegodon trigonocephalus, Elephas* cf. *namadicus).* If indeed these strata belong to the Notopuro stage and not to the underlying Kabuh Layers, which is still questionable, these basal conglomerates of the Notopuro stage belong indeed still to the Middle Pleistocene.

The upper border of the Notopuro period of strong volcanic activity is also still a point of discussion. Observations of DUYFJES (1936) near Trinil indicate that the high terrace of the Solo River is younger than the Notopuro breccias, and separated from the latter by an indistinct unconformity. This high terrace contains near Ngandong in the Solo cross valley, North of Ngawi, the upper-pleistocene Ngandong fauna with *Homo neanderthalensis soloensis.* The Watualang deposit, East of Trinil, contains also an upper-pleistocene vertebrate fauna; according to (he field relations it is quite possible that the Ngandong deposit belongs to the upper part of the Notopuro stage and not to the high terrace. If so, the Notopuro stage reaches into the lower part of the Upper Pleistocene, having more affinities to the Ngandong stage than to the Trinil stage.

Moreover, the Notopuro breccias can be correlated with the Djombang breccias in the Surabaja area to the East, and the Linggopodo breccias in the Bumiaju area to the West (see the discussion of the North-Seraju Range, later on). These breccias seem to belong to (the lower part of) the Upper Pleistocene in the stratigraphical column.

On account of these data the following can be said about the age of the Notopuro breccias. They are separated by an unconformity from the underlying middle-pleistocene Kabuh Layers, and also by an unconformity from the upper-pleistocene high terraces of the Solo River on top of them. Locally, e.g. in Sangiran and Baringinan, the deposition of the basal conglomerates probably begins already in the Middle Pleistocene. On the other hand, the upper part of the Notopuro Beds near Watualang seems to contain a Ngandong fauna. Therefore, the Notopuro stage probably comprises the upper part of the Middle-Pleistocene and the lower part of the Upper Pleistocene.

For the sake of clearness in the stratigraphy and because these finer stratigraphical distinctions cannot be maintained for the whole area, they will be considered as Upper Pleistocene in the following pages.

The age assigned by the author to the Notopuro breccias differs somewhat from the opinion of VON KOENIGSWALD, who places the Notopuro breccias in the upper part of the Middle Pleistocene (table 13a). However, these differences are only of importance with respect to the correlations with the international stratigraphical scheme and the glacial chronology. The crucial point is the position of the Watualang deposit. It is not of direct importance for the regional sequence of geological events, as the position of the Notopuro breccias in the local stratigraphical column is quite clear.

The tektites and paleolithic implements, collected by VON KOENIGSWALD in the Sangiran area, are mostly found on the crosional surface separating the Kabuh Layers and the Notopuro breccias. This surface is best exposed on the NE side of the Sangiran dome near Grogol or Grogolan (VON KOE-NIGSWALD, 1935 e).

If these tektites belong to the group of Indo-Malaya-dianites (found in Billiton, Borneo, Philippines and Indo-China), which is quite probable, the age of this swarm is thus fixed as Middle Pleistocene (see also H. OTLEY BEYER, 1942).

As stated above, the high terraces of the Solo River near Trinil are separated by an unconformity from the Notopuro breccias. These terraces are still of upper pleistocene age. They contain already some ash layers of the youngest volcanic activity. Thereafter, in the Holocene, the young volcanic cones of the Solo Zone were built up (Young Lawu, etc.).

Some indications about the older strata underlying the Ngawi Subzone arc provided by the blocks, erupted by the extinct **mud volcanoes in the centre** of **the Sangiran dome.** Among them are found:

Old-andesites; *Camerina-limcslone,* and *Discocyctina*-limestone (both Eocene); polymict conglomerates (with components of chert, aplite, aplite-granite, granite, quartz-ite, sandy shale, feldspar) (Eocene?); conglomeratic limestone with *Discocyclina, Pellatispira, Camerina* (Eocene); a single sample of *Lepidocyclina-Yimestone* (Miocene); marly, sandy and hard fragments of Globigerina-limestone, with smaller Foraminifera and no *LepidocycHna* (Pliocene).

The fact that both eocene and pliocene rock fragments are abundantly present, but the Miocene has only been established in one instance, indicates that the Miocene, developed as a thick geosynclinal deposit in the Kendeng Zone, wedges out southward towards the gcanticlinal axis of Java in the Solo Zone.

Folds in the Ngawi Subzone, connected with the Lawu Complex.[5]) The youngest folding of the strata in the Ngawi Subzone occurred after the Notopuro breccias. Folding of these breccias to the West of the railway from Surakarta to the North has already been discussed in relation with collapse of the Soropati and Merbabu volcanoes. Immediately East of this railway another group of folds and domes is found. It begins **immediately North of Surakarta.** The northeastern part of the town is traversed by a WNW-ESE fault, and North of this fault the Notopuro Layers are pressed up. The Solo River has formed an alluvial plain South of this fault, the town of Surakarta has been built in this plain. During water floods the drainage is still impeded by the low hilly country of Notopuro breccias at the northern side of the fault, so that a special flood canal ("Bandjir" canal) had to be constructed along the northern border of the town. The lefthand tributaries of the Solo River could maintain an antecedent W-E course across these hills, cutting through the Notopuro breccias into the underlying Kabuh Layers. In these exposures a sharp unconformity can be observed between these two strata (fig. 278). The gently warped Notopuro breccias dip westward at the West flank near the railway with a flexure-like bent (dips up to 5° W). One kilometre to the East of this flexure an olivine basalt layer issued in one of the E-W river gullies. This basalt flowed 1.2 km westward from its centre of eruption near Tjem-plukan, with a grade of 1 : 150, and 5 km eastward with a grade of 1 : 125. After this eruption the river cut its bed deeper into the underlying Kabuh Layers. This outflow happened shortly after the doming up of the Notopuro breccias. (A similar outflow of olivine basaltic lava on top of the Onto dome has already been mentioned on p. 565). The doming up of this southern portion, immediately North of Surakarta was due to a compressive force from the East (steep West flank!).

The next culmination is that of the **Sangiran dome,** in which the anticlinal axis has a SSW-NNE trend with a steeper WNW flank. Here the com-pressive force came from the ESE. The core of this

[5] See also map, fig. 268 on pl. **34**.

dome was exposed by erosion of the antecedent Tjemoro River. Its stratigraphy has been treated in the preceding pages (p. 565-567).

Farther North we find the **Gemolong dome** with a WSW-ENE trend. Its North flank is a steep flexure or even an upthrust; the Notopuro breccias are here in a vertical position. [6]) In the core of this dome pliocene strata are exposed: unstratified white *Globigerina*-marls of the Lower Kalibeng, succeeded by the Upper Kalibeng horizons (Klitik *Globigerina*-limestone, Sonde-marls, *Balanus*-limestone). These marine strata are unconformably covered by the Notopuro breccias which begin with 5-10 m of coarse, andesitic conglomerates and tuff-sandstones. Neither Putjangan nor Kabuh Layers are exposed in this dome. The *Globigerina*-marls of its core are thrust against the Notopuro breccias of its North flank by a compressive force from the SSE or SE.

The Gemolong axis can be traced eastward to the **Bringinan anticline,** which belongs already to the South flank of the Kendeng anticlinorium.[7]) Here only a thin strip of Black Clays of the Putjangan stage is exposed between the *Balanus*-limestone and the overlapping Notopuro breccias.

East of Bringinan, near **Gesi,** the South flank of the Kendeng shows another virgation, plunging southwestward under the Ngawi Subzone. The Notopuro breccias overlap the folded marine strata of the Kendeng, and the former are also slightly warped in the western plunge of this anticline. Apart from that warping, the Notopuro breccias dip gently southward from the flank of the Kendeng Ridge towards the central axis of the Ngawi Subzone.

The folds and domes in the Notopuro breccias from Surakarta to Gesi were formed by a compressive force, which radiated from the Lawu volcano in the South, viz. directed to the West near Surakarta, to the WNW in Sangiran, to the NNW in Gemolong and to the North in the South-flank of the Kendeng. These folds are situated at a distance of 35-45 km from the present summit.

Moreover, two more folds of presumably post-Notopuro age are found on the northern slope of the Lawu volcano itself, that is at the southern margin of the Ngawi Subzone, the Munggur anticline and the Gamping anticline.

The **Munggur anticline** on the NW flank of the Lawu is situated at a distance of 28 km from the summit; breccias of the Old Lawu (belonging to the Notopuro stage) form a NE-SW anticline with a steeper NW flank, bulging forth from the smooth slope of the young Lawu cone.[8])

The **Gamping anticline** lies on the North flank of the Lawu at a distance of 15 km from the summit. Here *Globigerina*-limestones resembling the upper-pliocene Klitik limestones dip 20° N; these limestones overlap a core of augite-hornblende andesites (G. Gelendangang 482 m) which resemble the volcanic constituents of the Banjak Beds (younger Miocene) in the Kendeng Zone. This situation indicates that the lower-pliocene marine strata of the Kendeng Zone wedge out southward, towards the axis of the Java-geanticline (situated in the Solo Zone *sensu stricto).* Lahars of the young Lawu cone bury the contact between these Gamping limestones and the neighbouring Old Lawu volcanic. No other strata crop out between the limestones and the Notopuro breccias, so that in the Gamping anticline also the Putjangan and Kabuh Layers are probably absent. These formations are restricted to the Ngawi Subzone.

Thus we see that the compressive forces radiating from the Lawu centre are also manifest in the Munggur- and Gamping anticlines at the North foot of the Lawu.

Now the **structure of the Lawu Complex** proper will be analysed more closely.[9]) This volcanic complex was built up in the central part of the Solo Zone (= Solo Zone *sensu stricto).* We can distinguish an older part of the volcano, deeply carved by erosion, and the more or less smooth surface of a younger cone. The older part of the volcano corresponds in age with the volcanic Notopuro breccias in the Ngawi Subzone North of it. This Old Lawu volcano is cut by a large crescentic rift, convex to the North, and filled by young Lawu vol-canics. The high road from Surakarta via Karang-anjar, Tawangmangu, and the Tjemorosewu pass (1,887 m) to Sarangan follows this grabenlike depression.

The southern border of this rift extends WNW and ends in the WNW-ESE trending transverse fault of Surakarta.

The Tjemorosewu rift is narrowest East of Tawangmangu (1 km wide) and widens from this settlement westward (about 5 km wide East of Karanganjar).

South of the Tjemorosewu graben follows a narrow horst of the Old Lawu volcano (Sidoramping, 2,131 m) and then another graben is found, partly filled with the young Djobolarangan cone (2,298 m). This graben wedges out westward, ending South of Tawangmangu. Farther South we find the southward slope of the Old Lawu volcano, where the Kukusan (1,925 m) perhaps represent a separate eruption centre of the Old Lawu volcanism. This southern slope forms the plain of Djatisrono (418 m) in the Blitar Subzone. Finally, it abuts against the escarpment of the Southern Mountains (Kambengan Range).

The eastward extensions of the Tjemorosewu-and Djobolarangan graben are completely buried under young volcanic products, but they are marked by young parasitic eruption points (crater lakes of

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[6] See section III, fig. 269 on pl. **28**.

[7] See section VI, fig. 269 on pl. **28**.

[8] See section V, fig. 269 on pl. **28**.

[9] See map, fig. 268 on pl. **34** and section A-B of fig. 280 on pl. **28**.

Sarangan and Telogowuro, East of the Tjemo-rosewu, and the small volcanic cones SE of Magetan and SW of Parang).

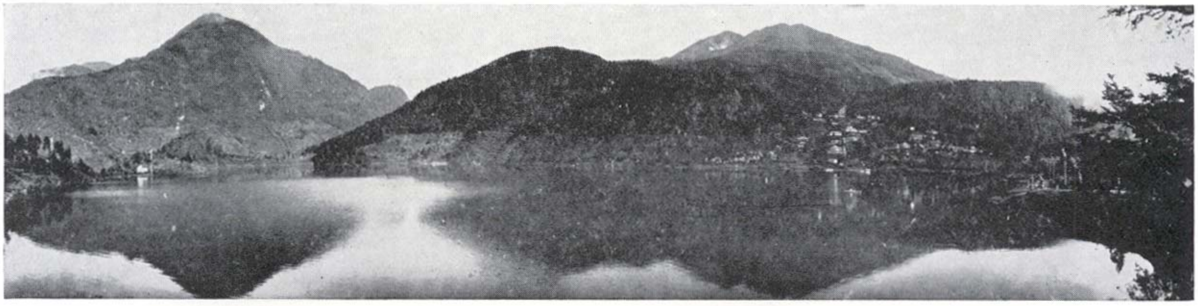

FIG. 279. *Photo of the crater lake of Sarangan.*
To the left the Sidoramping horst, and in the centre and background the young Lawu.

It appears from this analysis of the volcano-tectonic structure of the Lawu Complex, that the Old Lawu volcano has been subjected to tcnsional forces, so that E-W trending, graben-like rifts were formed. Thereafter these rifts were partly sealed by young volcanic activity (young Lawu, Djobo-larangan).

This tensional faulting of the Lawu Complex is probably a complementary process of the com-pression of its northern foot in the Ngawi depression (see fig. 280 on pl. **28**).

FIG. 280 on PLATE 28. *Section A-B across the Solo Zone between Gcsi (South flank of the Kendeng) and the Lawu Complex.* (For location and legend see map of the Sura-karta area, fig. 268 on pl. **34**).

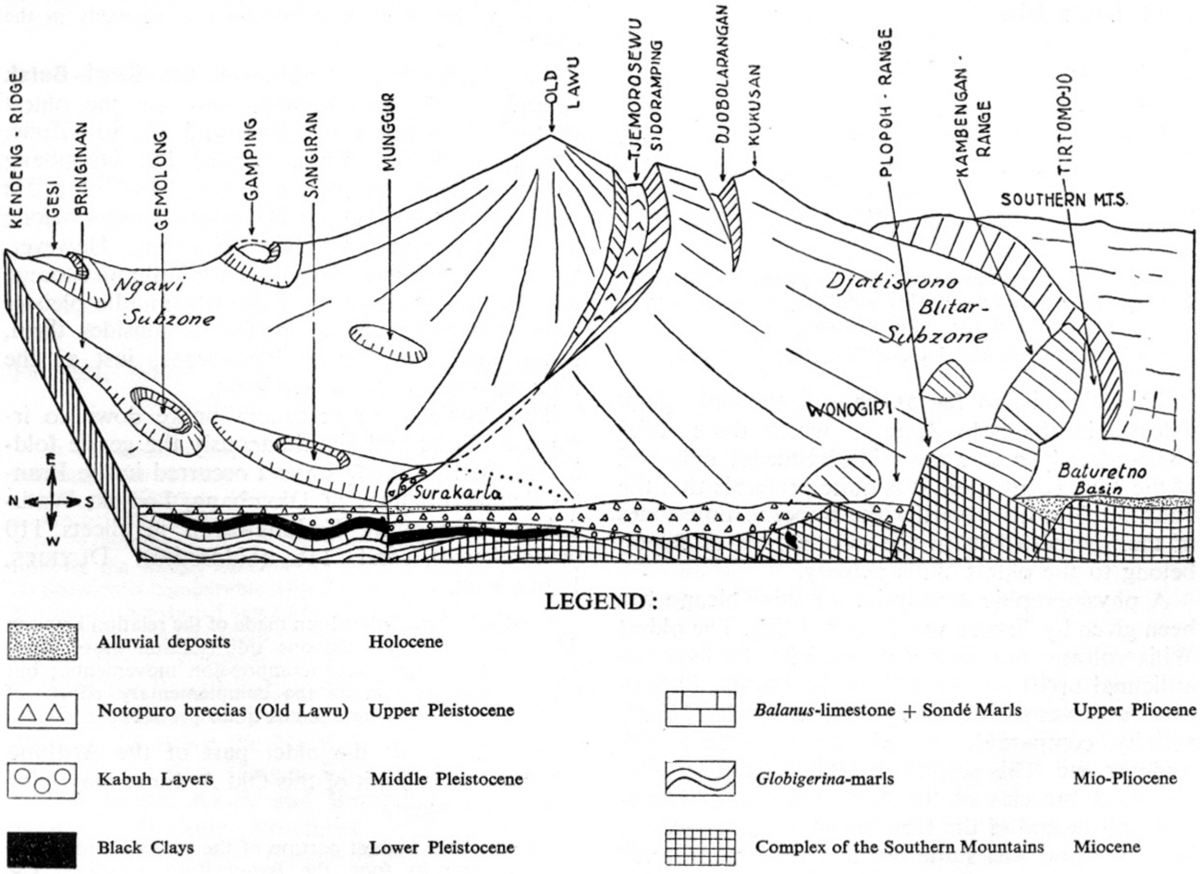

FIG. 281. *Schematic tectonogram of the volcano-tectonic collapse of the Old Lawu volcano at the end of the Notopuro period.*

This section shows that the Old Lawu Complex probably collapsed by the force of gravitation, and that its northern portion slid towards the North, thereby compressing its northern foot and foreland deposits. The series of domes in the Ngawi depression, beginning at Surakarta, North of the transverse fault, and arranged "en echelon", has been pressed up by the compressive force which radiated from the highest and heaviest part of the Old Lawu cone towards the adjacent low land.

This collapse at the end of the Notopuro period is shown in the schematical tectonogram of fig. 281.