CHAPTER VI

FAULT ZONE ROCKS.

Mention has been made of the fault zones in the area, in the section on structure (page 37). The cataclastic effect, due to faulting, has been responsible for the development of certain peculiar varieties of metamorphic rocks in these fault zones. The crushing of the rocks, due to faulting, has resulted in the development of cataclasites, mylonites and schists. All these are described under the heading, "Fault Zone Rocks.

At least five to six fault zones of mappable sizes have been observed in the thesis area, besides numerous local minor fault and shear zones. A brief descriptions of these faults is given hereunder:

1. About two furlongs N 20° W of the Nampuram Temple, a fault zone or shear zone has been observed producing a narrow zone of breccia parallel with the fault, which trends N 62° W - N 80° W. Here, there is an exposure of one thick band of ferruginous grit trending N 60° W - N 80° W, dipping at high angles of 78° SW. A thin dolerite dyke of about one and a half foot in width trending N 70° W, has come up along this fault zone and has got itself mixed up with the fault breccia. This fault zone follows most of the major fracture patterns of the area.

2. About one and a half mile northwest of the dam, crushed ferruginous rocks crop out with a linear trend striking N 50° W and dipping 62° SW. The ferruginous quartzite is not banded, but is highly crushed into brecciated material, though at places banded nature is imparted due to the parallel veins of quartz.
At places slickensides are noticed in the quartzite, where it is polished into a smooth, glazed surface often with rooving. Here and there, thin plates of chlorite schist are found as intercalated bands. It is often compressed into thin platy bands, the width of which varies from a thin stringer of a centimeter or two up to a foot. At some places, the ferruginous material predominated over quartz and it has weathered into a smoky, dark and charred material; occasionally, this material is associated with yellowish, reddish and brownish limonitic matter.

3. About half a mile southeast of this fault zone, there is another fault zone of the same nature as above is encountered in the midst of amphibolite and chlorite schist in the valley about one mile northwest of the dam.

4. About one mile north of Konamanayanipelle, a peculiar rock type resembling a feldspathic quartzite is met with, striking N 50° W with nearly vertical dip and has a width of about twenty five feet. The strike of this rock type is different from the general strike direction of the rock types of this area. Strictly speaking this rock is a mixed type consisting of admixtures of several rock types. In it, quartzitic, feldspathic, granitic and at a few places dark dioritic material are intimately admixed and traversed by thin veins and veinlets of cherty, trapshottened material. Here and there, thin epidote veins are also seen. Often, the rock gets split along cherty bands which constitute the plane of easy parting for the rock type. Such an intimate admixture of various rock types along narrow zone with a linear trend appear to be positive indication of the existence of a fault zone. The other rock types of this area terminate
abruptly against this crush breccia, which has enabled to demarcate a fault zone in this area.

5. About half a mile northeast of Konamanayanipalle, there are hill ranges striking N 30° W. These are composed mostly of fine grained, tough and compact amphibolites traversed by a network of bands of fine grained, hard, compact, impure quartzite. There is a caught up patch of chlorite schist inter-banded with the impure quartzite. The chlorite schist is often compact and tough, because of its intimate admixture with siliceous material. This chlorite schist presents directional strike N 65° W, dipping at 70° NE. This trend is almost at right angles to the strike direction of amphibolite. Probably, this strike of the chlorite schist may be due to the parting of the rock along one of the s-planes. The chlorite schist dips eastwards which again opposes the directional dip of the other rock types. This can be interpreted as a shear zone or fault zone along which the otherwise structureless amphibolite has been converted into chlorite schist by a process of regional metamorphism due to the frictional movement along the fault plane. Incidentally, the strike of the chlorite schist is parallel to the northwesterly striking dolerites of the area.

6. To the north and northeast of Konamanayanipalle, the amphibolite bands end abruptly against the banded gneisses and beyond the banded gneisses, there is a horizontal shift of the trend indicating faulting (?). The North Canal runs just between these two dislocated bands. This sudden discontinuity in the trend, both in the field and in the map— in the field in the form of discontinuity of ridges and in the map in the form of abrupt termination of rocks against a line—is taken to indicate fault-
ing. These two ridges are shown to be continuous in the topo-sheet, as they are enclosed within the same closed contours, whereas actually in the field, they form separate but parallel ridges. However, this discrepancy has been rectified while mapping. Though the evidence of discontinuity of the trend is visible, the actual plane of faulting could not be laid in the absence of other positive evidence.

Of all the above, the first four fault zone rocks, in general, show similar characters except for a few local variations. All the fault zone rocks have varying amounts of ferruginous matter traversing as veins and veinlets filling up the cracks. The iron oxide solutions might have acted as lubricating material for the slip zones, and the presence, here and there, of rocks with pronounced schistosity and black slicken-sided surface, bear testimony to considerable shearing. However, direct evidence of the directions and sense of movement involved in the faulting have not been found. Orientation of the net slip also could not be determined. In general, discontinuity of lithologic types derived from different formations is a characteristic feature, that can be attributed to these fault zones. At certain places, the rocks occurring within the fault zone seem to have been derived from the adjoining granite, but when the rock is rolled and milled to the extreme, it becomes difficult or even impossible to establish whether these have been derived from the granitic rocks.

Philips (1965) has described the structures developed in a silicified shear zone and has traced out gradual and complete variations from foliated granites through granulated and partly silicified rocks into banded quartz tectonites over several hun-
The fractures are also filled up with chalcedony, which occurs as thin plates or veins in the fracture planes. The fault breccia with varying proportions of incorporated dyke material is only of local occurrence. Further northeast, it runs as a continuous stretch of linear band, occasionally thinning or broadening, at places with its conspicuous appearance due to the occurrence of detached boulders and pebbles and other fragments of varying sizes. Here, no schistose structure is seen at any part of the fault zone.

In the fault zones 2 and 3, the deformation seems to be more pronounced with extensive crumpling. Schistose rock is locally developed here and there. Also the slip zones are characterised by smooth, striated mylonite and gouge material.

The most common type of rock in these fault zones may be referred to as cataclasite. It is a fine breccia with included fragments of nearly opaque quartz of varying sizes, generally less than two centimeters across. It appears as if the fragments are embedded and welded within a fine matrix. This sort of appearance is given to the rock, because of the uneven and patchy distribution of the inter- and intragranular iron oxide material, which has left island fragments of dust-free quartz. Sometimes, the veins and veinlets cut across the included quartz fragments or the iron staining of the groundmass may be seen to penetrate the finer-grained parts of the included fragments. Sometimes, the rock may be composed of closely packed white or smoky quartzite pebbles set in a darker, fine grained matrix. The largest of the quartzite pieces is 6" in length, their average length being about 2 inches. These included fragments are rounded or subrounded with smooth surfaces. In general, the
fault zone rocks appear to be of heterogeneous character. This heterogeneity is still more clearly and pronouncedly evidenced under the microscope. Though, these are very heterogeneous, these possess very simple mineralogical assemblage.

In most of the sections, it is entirely composed of quartz only of quartz and feldspar only, in some, quartz being dominant while in others, feldspar grains are more abundant. Most commonly, quartz and feldspar grains seem to be segregated and in a few cases, those minerals are evenly distributed. Microveins and veinlets, in some sections, exhibit erratic distribution either full of simple or anastomosing veins cross-cutting the grains and traversing the whole rock, or partly or completely devoid of them. Notable disparity in the grain size of both quartz and feldspar is the striking feature. Similarly, widely varying degrees of alteration and deformation are other most striking features. The textures and structures seen are those, that result from cataclastic deformation and recrystallisation.

Quartz:

Notable disparity in the grain size and undulose extinction are the general features attributed to the quartz of these rocks. Because of its brittle nature, it is ruptured into angular fragments. Most of the grains are complexly fractured and sutured and traversed by mostly quartz and iron oxide veins and occassionally by epidote and chlorite veins.

There is a wide range in grain size. There is every gradation between the cryptocrystalline quartz and large angular fragments. The fine granules, which form the microcrystalline mosaids, are generally less than 0.02 mm. Coarse quartz grains occur as
irregular patches, seams and single crystals set in a fine
grained and/or cryptocrystalline matrix which made up of quartz,
plagioclase and iron oxide material and rarely chlorite. The
course grained quartz is drawn out into lense shaped and spindle-
shaped bodies which show irregular, mosaic or mortar texture,
with pronounced undulose extinction.

**Deformation of Quartz:**

The quartz grains show different degrees of deformation and
undulose extinction. In some grains, the strain shadow uniformly
passes inward to middle part of the grain from its borders or
from the middle outwards to the borders, depending upon whether
the microscope stage is rotated in the clockwise and anticlock-
wise direction.

The strain shadow, in some quartz grains, passes from one
side of the margin to the other.

In a few other grains, which appear to be bent in a slightly
curved way, the wave of the shadow sweeps like a "fan" in an
arcuate fashion.

In the grains, which are highly deformed, pronounced undulose
extinction is noticed in which case, it does not conform to any
of the above-mentioned types, but shows a combination of these
patterns. It will be patchy, fibrous or confused shadows.

The unaffected grains and the recrystallised grains and
aggregates appear fresh and show normal extinction.

Bailey, et al (1958), from an optical and X-ray study of
the nature of the naturally occurring deformed quartz, have
explained and correlated the results by a theory involving dis-
locations and polygonisation, whereby the bent crystal is trans-
formed into a number of elongate, relatively perfect crystallites inclined to one another at small angles and separated by regions of atomic misfit. They have explained the undulose extinction as an optical expression of the results of bent gliding and polygonisation.

Undulose extinction includes, as is classified by De Hills and Corvalan (1964), two phenomena of which one is the continuous undulatory extinction in which extinction is microscopically gradual within crystals or sectors of crystals, while the other is discontinuous undulatory extinction, in which crystals consist of the sharply bounded sectors or bands of slightly different optical orientation. According to the above workers, a combination of these two phenomena displays internal continuous undulose extinction in sharply banded sectors, while Bailey et al (1958) and Turner and Weiss (1963) attribute discontinuous undulose extinction as resulting from partial annealing of continuous undulatory extinction.

The following procedure as given by De Hills and Corvalan (1964) has been followed in determining the amount of undulose extinction in quartz grains.

The grain is set in the position of highest birefringence and then the microscope stage is rotated until first clear evidence of undulatory extinction appears. The reading on the stage is noted. Then the stage is further rotated until it passes through complete extinction and further undulatory extinction bands disappeared, the reading on the stage is noted. The angle measured gives the amount of undulose extinction. Like this, the undulose extinction for about 150 grains has been measured and given in the Table 19.
**Table No. 24.**

(Numerals in the brackets indicate the number of quartz grains giving identical values.)

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Section No.</th>
<th>The amount of undulose extinction in degrees.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>Fp-FZ-1</td>
<td>2456</td>
</tr>
<tr>
<td></td>
<td></td>
<td>36, 72, 61, 68, 43, 45(2), 64, 71(3).</td>
</tr>
<tr>
<td>3.</td>
<td>EAV-XY</td>
<td>2458</td>
</tr>
<tr>
<td></td>
<td></td>
<td>49(2), 42, 34, 44(2), 35, 52.</td>
</tr>
<tr>
<td>4.</td>
<td>Fp-X</td>
<td>2316</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30, 42, 43, 45(2), 48, 33(2).</td>
</tr>
<tr>
<td>5.</td>
<td>EAV-72</td>
<td>571</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30, 45, 41(3), 37, 35, 47(2).</td>
</tr>
<tr>
<td>6.</td>
<td>EAV-FZ</td>
<td>2490</td>
</tr>
<tr>
<td></td>
<td></td>
<td>51, 83(2), 76, 52(2), 44, 59, 62(3), 38, 55, 64.</td>
</tr>
<tr>
<td>7.</td>
<td>EAV-FZ</td>
<td>2484</td>
</tr>
<tr>
<td></td>
<td></td>
<td>57, 63, 47, 53(4), 77, 71, 74(2), 45, 52, 58(2).</td>
</tr>
<tr>
<td>8.</td>
<td>Fp-CQ</td>
<td>2601</td>
</tr>
<tr>
<td></td>
<td></td>
<td>52(2), 57, 88, 51, 82(2), 49, 60, 42, 38(4).</td>
</tr>
<tr>
<td>9.</td>
<td>Fp-8-CQ</td>
<td>2596</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50, 56, 48, 75, 72(2), 90, 32, 31.</td>
</tr>
<tr>
<td>10.</td>
<td>Fp-CQ</td>
<td>2610</td>
</tr>
<tr>
<td></td>
<td></td>
<td>63, 78(2), 53, 43, 69, 85, 48, 73(2), 68.</td>
</tr>
<tr>
<td>11.</td>
<td>Fp-CQ</td>
<td>2604</td>
</tr>
<tr>
<td></td>
<td></td>
<td>52, 83, 46(3), 60, 51(2), 74, 56.</td>
</tr>
<tr>
<td>12.</td>
<td>Fp-8-CQ</td>
<td>2594</td>
</tr>
<tr>
<td></td>
<td></td>
<td>57, 64, 48(2), 62(3), 63, 71.</td>
</tr>
<tr>
<td>13.</td>
<td>Fp-CQ</td>
<td>2612</td>
</tr>
<tr>
<td></td>
<td></td>
<td>65(2), 39, 44(3), 70.</td>
</tr>
<tr>
<td>14.</td>
<td>Fp-CQ</td>
<td>2613</td>
</tr>
<tr>
<td></td>
<td></td>
<td>65(2), 38, 44(3), 54(2), 70(2).</td>
</tr>
<tr>
<td>15.</td>
<td>Fp-CQ</td>
<td>2614</td>
</tr>
<tr>
<td></td>
<td></td>
<td>53(2), 44, 65(2), 62, 55.</td>
</tr>
</tbody>
</table>
De Hills and Corvalan (1964) interpret the marked difference in the intensity of the undulatory extinction as the result of the degree of tectonic deformation of the granitic rocks of different ages and thus, from a microscopic study of primary quartz grains of granitic rocks of known radiogenic ages, they show a significant correlation between the intensity of the undulatory extinction in this mineral and the age of these rocks, but from the study of the undulose extinction of quartz grains of the fault zones of the thesis area, as is evident from the Table 24, such a correlation cannot be established. It is well known, that undulose extinction in quartz is a strain effect, the mechanical feature, which depends entirely on environmental factors. Thus, the intensity of undulatory extinction appears to be a reflection of the environmental history of the rock as a whole, does not seem to be significantly related to its absolute age.

The quartz fabric, induced as a consequence of deformation seems to have resulted in two ways, firstly, granulation by deformation and secondly, granulation by recrystallisation, but the relative amounts of granulation by these two processes cannot be determined. During the course of deformation, strain shadows make their appearance at the strained portions of the grain, thereby, rendering it an undulant grain. The rupture of this larger grains seems to have taken place between these undulose bands. In some grains, these undulose bands show thin lines of minute quartz granules, before the overall rupturing of the whole grain takes place. Recrystallisation also produced granulation. In this case, the quartz grain enlarges and gets granulated, first at the peripheral portion; as it continues, the
large grain is ultimately ground down to a mosaic of fine granules. Again the fine granules, thus produced, seem to coalesce forming larger grains. Thus, the two processes, granulation by deformation and granulation by recrystallisation involved in developing the quartz fabric appear to be "cyclic". However, in the initial stages of stress, granulation by deformation is prevalent, while in advancing stages, granulation appears to be due more to recrystallisation. The grains, which suffered a high degree of deformation display deformation lamellae are replaced by Boehm lamellae or relic lines of inclusions which are clearly seen when mounted on the Universal Stage and at an appropriate tilt.

Mutual contacts between quartz grains are normal, sutured or exhibit a denticulate pattern. The quartz shows a clear cut tendency to penetrate feldspar grains at random direction cutting almost across the feldspar grains including along the twin planes. Thus, extending from the quartz grains are numerous small branches, barbs, prongs, delicate apophyses that penetrate feldspar. Sometimes, these barbs and prongs and such other quartz protruberances corrode and round the feldspar grains and locally have surrounded them. The characteristic cataclastic deformational textures reveal that under conditions of moderate to high pressure solution, a much greater solubility of quartz when compared to feldspar. The shearing stresses have induced solid flow in which solution and redeposition have been quite noteworthy, although mechanical disintegration is dominant over chemical decomposition.

Plagioclase:

Plagioclase, like quartz shows very wide variation in grain size.
size from the minutest particle sometimes finer than quartz both in clusters and individual grains.

The grains are irregular in outline and the porphyroblasts generally have ragged edges. The grains are very rarely fresh and clear. Most of the grains are corroded with alteration commonly to sericite and kaolinite; such an alteration in general varies from slight turbidity to an intense development of clayey and micaceous material, sometimes to clinozoisite and epidote. Just as they show all degrees of alteration, they also display all degrees of deformation in a single thin section. The plagioclase, in general, possesses the most fine-textured twinning with numerous, narrow and well-defined lamellae. In some grains, however, the sharpness of the twinning lamellae fades out. The cataclastic deformational features in plagioclase are observed to be in varying degrees and in varying sorts (Plate XIII, Figs. 1-6).

Because of the strong stresses to which the rock was subjected, the effects are seen to be intensive and extensive crushing and shattering of feldspar grains besides the development of tension and pressure cracks in them. The feldspar grains are broken across and along the cleavage and twinning planes. They also yield conforming to the grain boundaries and pore spaces. In some grains, micro-faulting is displayed in the twinning lamellae which are off-set, and step-like cracks are developed diagonally across the cleavages. Most of the grains occur as crumpled, elongated wisps, in some cases frayed apart along cleavage planes and twinning planes and mostly infiltrated with secondary quartz which occurs as small branches, barbs, prongs and deli-
cate apophyses and penetrating the feldspar grains along healed fractures. In many of the thin sections, the plagioclase occurs in a net work, which forms an intricate and ramifying maze. The feldspar grains which occur as segments or strands of this net work are thin or long and vein-like while some are straight, long or short, but most commonly they are extremely irregular and uneven. Some feldspar grains occur as a connected net work while some are isolated grains. Some feldspar may occur locally interstitial to the quartz grains but in many cases the recrystallisation has advanced to such a degree that the interstitial relations have been obliterated. Cataclastic texture occurs transitional between crystals with mosaic borders to aggregates of angular fragments which beyond doubt are derived originally from single individuals. In some cases, the slightly displaced pieces are recommenced by fresh plagioclase which extinguishes over small areas at the same time and is usually more transparent than its original material. It is generally in parallel orientation with the broken grains. The secondary feldspar is identified by relatively clear appearance and the twin lamellae of the central portion end abruptly at the contact with the secondary feldspar. Further the secondary feldspar may also appear as narrow, untwinned rims which in places may be continuous around several adjacent, closely packed individuals. Feldspars sometimes shows undulose extinction and the same is, sometimes, seen in the secondary feldspar rim, also indicating the extent to which the secondary feldspar enlargement reproduces the optic orientation of the grain along which it is developed.

In some cases, the quartz and plagioclase grains are mingled, forming thus a mosaic of these two minerals, together with secon-
dary micaceous and clayey material derived from the alteration of the feldspar. The amount of feldspar and the relative size varies considerably. Accordingly, the textural relations become less distinct and ultimately obliterated in proportion to the degree of recrystallisation.

**Inclusions and Alteration Products:**

Occasionally, the feldspar grains contain tiny, rounded and oval shaped and irregular grains of quartz. Sometimes epidote grains are seen enclosed within the larger plagioclase plates and often, they are found confined to the twin planes. Minute specks or dust of opaque ore are found to be peppered.

Almost all grains encountered in thin sections are extremely turbid, sometimes so turbid, as to mask the twin lamellae. Feldspars are most commonly sericitised and kaolinised. Sericite and sericitised feldspar are common but unaltered grains are rare or absent.

Almost all the plagioclase grains are extremely altered to highly turbid grains, densely flooded with minute specks, laths and flakes with micaceous minerals and clayey products. Amongst these alteration products, the micaceous minerals which are transparent with low interference colours are recognised as sericite, while the grains which appear white or opaque under reflected light are identified as kaolinite. By using such discrimination, it has been observed that sericite constitutes the largest amount among the altered products. Sericite occurs as minute specks, scales, fibres or shreds. It is further characterised by straight extinction variation in the relief under polarised light on rotation of the microscope stage, strong double refraction and
elongation parallel to the slow ray. The optic axial angle measured on the tabular and elongated grains is found to be very low. Sericite, in the altered plagioclase, is clearly seen, because when the plagioclase grain is in extinction position, the sericite will be illuminated with interference colours, thus apparently giving a "twinkling effect". Sometimes, in the same section, both sericite and sericitised plagioclase occur; and unaltered plagioclase is rarer or absent.

Some of the plagioclase grains show thin, colourless rims around the grain borders. These rims appear quite conspicuously because of the fresh and clear appearance devoid of any such inclusion around a highly altered grain. Sometimes, when the grain is traversed by iron-oxide vein, it is similarly bordered on either side, and all along the vein by a thin clear portion of plagioclase. Probably, these grains may be called as the "plagioclase aventurines" referred by Neumann and Christie (1962).

**Plagioclase Twinning:**

The determination of plagioclase feldspars has been carried out in accordance with the method of Prof. Reinhard (1931).

Grains from 28 thin sections were determined on the 4-axes Universal stage and the results have been tabulated in Table 20.

The twin laws of deformed plagioclase are represented by only albite and albite ala B. Only two grains have shown pericline law. This indicates, that the twins with (010) twin plane are more resistant to stresses while twins with (001) twin plane are less resistant. This is also in accordance with the reported statistical analyses of twin law by earlier workers; the twins
with (010) composition plane are far more abundant than those with (001) composition plane.

**Cumulative Diagram:**

When cumulative diagram of the poles of the composition faces are plotted on table 2 of Reinhard, the cumulative points show a remarkable dispersal or strewing away of the poles from the curves. The dispersal of the poles has also been noticed by Homma (1932), Paliuc (1932), Barbeär (1936), Naidu (1954), Van der Kaaden (1955), Suwa (1956) and De Vore (1956). As was suggested by Barber, an attempt has been made to rectify this dispersal by locating the optic symmetry plane, instead of the morphological composition face, in normal twins. Inspite of this being resorted to, the scatter of the poles has still been found to be more or less of the same order. According to Campbell Smith (1928), the results of the poles of the twin axes are of a higher degree of accuracy than those for the composition planes. Accordingly, the poles of the twin axes, located by Nikitin and Berek's constructions, are plotted in Table 5 of Reinhard. Even in this case, the degree of dispersal is as pronounced as in the case of the poles of the composition planes. Barber (1936), has reviewed all the causes for explaining such a scatter and had attributed temperature as responsible for this phenomenon.

**Compositional Differences:**

Often, the deformed plagioclase has been found to show compositional differences in the contiguous twin lamellae. Such compositional differences have been recorded by Coulson (1932) and Emmons and Gates (1943). However, compositional differences varying between 5% - 10% are common, but in these deformed plagioclase, it is found to vary between 10% - 18%. Only Coulson
(1932) has observed compositional difference greater than 10%. Turner remarks, "A discrepancy between the values for composition as determined (by Universal Stage measurements) in different pairs of sub-individuals belonging to a single crystal... is by no means uncommon". This anomaly has been observed by other workers and this discrepancy appears more pronouncedly in the case of the mechanically deformed plagioclases.

Bradley (1953) attributed the anomalous optics in three ways:

1. Twin- and composition-planes diverge from the standard Reinhard stereograms;
2. Compositions determined from Universal Stage stereograms differs from that given by refractive index determinations;
3. Twin angles fall on or near the high temperature graphs of Kohler.

All the optical anomalies in plagioclase are attributed to structural variations and are considered to be due to order-disorder phenomena.

From the observations made on the plagioclase in this study of deformed rocks, certain doubts are cast on the validity of certain generalisations made by earlier workers.

1. Gorai (1951), has figured twinned grains to illustrate that twin laws could be inferred from the shapes of the grains. It is doubtful if it is possible to do so. The grains twinned after albite law and albite ala look alike. The pericline, however, has a characteristic appearance.

2. "The greatest uniformity is found in the sodic and calcic plagioclase, and the least uniformity in the intermediate plagioclase" (Emmons and Mann, 1953, p.46).
The greatest uniformity and least uniformity in the twinning lamellae are seen in the same specimen and in the same section. Sometimes, partly uniform and partly non-uniform twinning is seen. Hence, uniformity or nonuniformity of the twinning lamellae does not seem to reflect the composition of plagioclase.

3. "The relatively low viscosity of crystallising calcic rocks and the relatively high viscosity of crystallising sodic rocks is reflected respectively in the wide and narrow twin lamellae". (Emmons and Mann, 1953, p.46).

Wide and narrow twin lamellae are seen in the same slice, sometimes, in the same grain and also all gradations and transitions are seen. Sometimes, the width of the lamellae are widely varying. Such variations in width are seen both longitudinally and laterally; thus either the composition or the nature of the liquid (viscosity) from which the plagioclase has crystallised do not seem to control the widths of the lamellae, but seem to depend mostly, if not entirely, on the environmental as well as thermal history of the crystal.

"......the untwinned plagioclase is, in reality, unzoned plagioclase, for whatever reason, and is incapable of twinning" (Emmons and Mann, 1953, p.54).

An untwinned plagioclase may possibly originally be twinned, but twinning might have, later been effaced under the circumstances explained in the foregoing pages.

4. Christie (1962), has suggested a plagioclase thermometer. The principle of this geo-thermometer is given by Smith (1956), Mac Kenzie (1957), and Mc Connel and Mc Kie (1960). But under
the conditions resulting in the extreme recrystallisation and induce variations and irregularities in the composition, optics and structural state, it is a matter of doubt whether the plagioclase thermometer using structural state and anorthite content as variable is applicable for these feldspars of deformed rocks.

5. Further, no clue or indication is obtained from these mechanically deformed plagioclase grains, whether these are of clastic origin or inherited from a magmatic or pre-existing metamorphic phase because it appears that already existing twins are not maintained due to intense deformation. Similarly, certain twins are removed by changing over into untwinned state. Hence, it is a matter of doubt whether, "Pattern of Plagioclase Twinning as a Significant Property", as suggested by Tobi (1961& 1962) holds good for these deformed rocks. Probably due to this, Gorai (1951, p.890) mentions in a foot-note that rocks with marked shearing effects are excluded in plotting U:A:C ratios in various plutonic rocks. However, it must be pointed out that certain characteristic features associated with these plagioclases indicate as resulting from deformation of rocks. One point here merits stress and repetition that such doubts on the validity of the generalisations made by earlier workers with respect to plagioclase feldspar arise in so far as cataclastically deformed plagioclases alone are concerned.

**Microcline Twinning:**

Microcline generally occurs as twinned grains, sometimes shows either albite or pericline twinning. In sections parallel to (010) only a single set of pericline twinning lines are seen, while in sections parallel to the composition face of the pericline twinning, only albite twinning is displayed. Most commonly, the
grains show a combination of both these two types. Albite and pericline twinning, closely interwoven, gives a peculiar pattern, which is variously termed as "cross-hatched", "grid", "grill", "grating" or "tartan" patterns. This, when viewed under crossed nicols in a direction approximately parallel to both composition planes, the "cross-hatched" intersections are seen to be nearly perpendicular to each other.

The peculiar relationships between the two twin laws in microcline and their accommodation in the crystal structure are discussed by Laves (1950) and the relationship between these two types of twinning in microcline crystals are taken to be evidence that it first crystallised with monoclinic symmetry, that is above inversion temperature and subsequently became triclinic on cooling. The types of twinning seen in microcline are also exhibited by microcline microperthite.

**Transformation Theory:**

Michel-Levy (1879) regards orthoclase and microcline as identical, with the twinning in the former sub-microscopic, too fine to be determined even with highest power objective and this view seems to be confirmed by the fact that the two minerals give the same laue diagrams (Hadding, 1921).

In the potash feldspar structure, Barth (1959), recognises three extreme variants and all kinds of transitions amongst these variants differing in respect to the degree of disorder of the Al/Si distribution in its crystal structure. The three extreme variants are:

1. Sanidine which is disordered monoclinic, $K (Al, Si)_{4} O_{8}$.
2. Orthoclase which is partly ordered microcline, $K (Al, Si)_{2} Si_{2} O_{8}$.
3. **Microcline which is ordered triclinic, KAlSi$_3$O$_8$:**

Laves (1950), on the basis of crystal geometry, points out that the typical microcline twinning is indicative of inversion from an original monoclinic crystal, indicating that potash feldspar nearly always crystallises initially with a monoclinic symmetry. Later, Goldsmith and Laves (1954) have collected a large number of experimental facts, which enabled them to assume that the familiar cross-hatched microcline from magmatic, migmatitic and metamorphic rocks was formed by diffusive transformation from pre-existing monoclinic orthoclase. Barth (1956) suggests that natural potash feldspar at about 400°C, (corresponding to the temperature of formation of certain gneisses) grew as a monoclinic orthoclase and subsequently at a still lower temperature, he postulated the development of microcline by a process of diffusive transformation upon cooling into a more ordered structure of low to high triclinicity (at 400°C, partly disordered structure of intermediate triclinicity) is believed to impart the familiar cross-hatching in microcline. Heier (1957), expresses that the grating structure is present not only in most triclinic microclines but even in those of intermediate triclinicities also.

**Microcline Structure Attributed to Stress or Dynamic Cause:**

About the microcline grating, Alling and Spencer are of the opinion that the local stresses set up in the crystallising framework would encourage the inversion of the orthoclase to microcline form. But, most writers emphasise the importance of the influence of stress or the dynamic forces in the formation of microcline structure. Thus Harker, points out that, "The conversion of orthoclase to microcline or the setting up of
microcline structure in orthoclase has been attributed to dynamic causes. Rosenbusch remarks, the fact that microcline is almost invariably confined to older eruptive rocks which have been subjected to processes of faulting and pressure, together with the observation that the microstructure of the microcline when it has experienced strong pressure leads to the supposition that microcline structure is a pressure phenomenon.

Kohler (1949), similarly observes that the change from monoclinic to triclinic form is aided by tectonic forces which, with increased intensity increases the courses of the exsolution albite and produces microcline grating. Similarly Chayes (1952), from the observations on the association of microcline with highly undulant or granular quartz in calc-alkaline granites attributes to shearing stress. The cross-hatched twinning in microcline of M.P.R. granite is also due to the shearing stresses (p.135).

In the microcline of M.P.R. granite the development of albite and pericline twinning lamellae in the feldspar is irregular, sometimes one and sometimes the other predominating. In certain orientations, only albite twin lamellae are seen confined to the margin of the grain. In others, they are seen at both the margins, their number increasing gradually towards the centre. The irregular twin lamellae distribution may be due to different strain effects on the crystal. Similarly the cross-hatching is also patchy, sometimes confined to the margin and sometimes confined to the centre of the crystal. In others, cross-hatching spreads all over the grain. It is significant to note that even in grains showing cross-hatching, patchy as they are, there are portions where only one set of lamellae has developed. In such cases, the
lamellae may be parallel to (010) indicating that albite twinning lamellae predominates over the pericline lamellae.

The appearance of albite blebs in microcline microperthite is also related to the orientation of the grain. In grains that do not show cross-hatched twinning either due to orientation or to the twinned nature according to albite or pericline laws, the blebs are clearly seen. In twinned grains, they become less clear probably because the albite blebs lie with their largest face parallel to the twin lamellae. The blebs occur as long needles in (100) and (010) zone. The distinctiveness with which the blebs present themselves decreases from the above zone to the zone in (001). Cross-hatching is marked in (001) plane in which the blebs occur as tiny dots and hence become indistinct. The grating structure with the quadrille pattern, sometimes, mask the already indistinct blebs seen in the (001) plane.

In the microcline of M.P.R. granites it has been noticed that twinning in a cross-hatched nature takes place in more than one way.

In some cases albite twinning lamellae seem to be first to develop in an untwinned grain.

(1) These albite twin lamellae start to grow on one side of the grain and spread quite across to the otherside by gradual and progressive increase in the number and size of twinning lamellae.

(2) The albite twinning lamellae start from both sides and also found in the middle and spread all over the grain.

(3) In some cases, it is observed that cross-hatched twinning start growing at one particular side and spread all over the grain by the simultaneous development of both albite and pericline twinning lamellae.
it appears that stress alone is not solely the factor to impart twinning and/or perthitic structure to potash feldspar.

Around inclusions (quartz, plagioclase with or without albite rims, biotite) in microcline, the pattern of twinning may remain unaffected or not. So in microcline, an inclusion does not seem to control either in the formation or elimination of twinning. In plagioclase it is found that inclusions tend to retain the twin lamellae, whereas in those where inclusions are not found, they are found to be effaced.

It appears that in microcline the elimination of twinning takes place in the same steps as it is introduced. However, the difference in that, when twinning is introduced, albite twinning lamellae appear earlier to pericline and when twinning is effaced pericline twinning lamellae are earlier to be eliminated.

Eskola (1951, p. 40 and 1952, p. 148) points out that untwinned microcline becomes cross-grated starting from edges or boundaries and the twinning lamellae are at once as large as they will ever grow. Similar observation has been made in the case of Rapakivi, while in the rocks of granulitic facies, he observes the grating development in a different way. According to him, the first stage of alteration of the clear orthoclase into microcline appears in the form of undulatory extinction. Gradually, extremely fine twinning lamellae appear in the most strained parts of the grain and finally the whole crystal is cross-hatched microcline, while the other specimens display only a well-developed quadrille structure. Thus, Eskola characterises rocks of a particular facies with a specific pattern of development of microcline twinning.

Since in granites, it has been observed that cross-hatched twinning in microcline takes place in more than one pattern, it can probably
not to be used as a criterion or characteristic for any particular mode of origin or type of facies.

Elimination of Twinning in Feldspars:

Buerger (1945, 1948) has formulated a general theory of twinning in crystals on structural grounds and draws a contrast between his theory and the theory of the French school, which is based on geometrical grounds. He distinguishes between growth twins, transformation twins and glide twins. The growth twins occur in stable forms, transformation twins in high-low temperature transformations and glide twins during deformation.

Petrographic literature of the last thirty five years includes a number of studies on occurrence, nature and origin of twinning in plagioclase of both igneous and metamorphic rocks. (e.g., Phillips, 1930; Coulson, 1931; Barber, 1936; Chapman, 1936; Donnay, 1943; Emmons and Gates, 1943; Turner, 1951; Gorei, 1951; Emmons and Mann, 1953; Suwa, 1956; Vance, 1961). Most of the authors have been interested in investigating the origin of twinning, they have looked for the cause of the twinning but nobody has ever given thought to the elimination of twinning except for an observation made by Vance (1961). Remberg (1961, p.11) mentions albite twins confined to the middle part, while on either side to are the untwinned parts. His explanation is that the feldspar has started to grow as a twinned nuclei but continued to grow in an untwinned state, due,probably, to rapid growth for a relatively short time just after nucleation, and a subsequent slower growth. In the course of the present study the author has observed that the effacing of plagioclase twinning has been brought about in more than one way (Fig. 4.04):
(1) In some plagioclase grains all the twin lamellae become bent and coalesce, ultimately producing an untwinned grain;

(2) In some grains, at one end, there is the development of secondary glide lamellae and these bend gradually until they merge into one broad lamella and the other part of the grain forms the second individual of the twinned grain.

(3) In some grains, there is a tendency for the reduction in the number, size, and continuity of twin lamellae, disappear, giving rise to an untwinned grain.

It is well known, that both plagioclase and potash feldspar, particularly microcline, are very prone to twinning, which is mostly a mechanical feature and a reflection of the environmental history of the feldspars. Twinning is initiated or developed in plagioclase by heating, as shown by experimental investigations (Scholler, 1941; Tuttle & Bowen, 1950; and Muir, 1955). So also, lamellar twinning in plagioclase notably (010) has been produced experimentally by straining crystals, which are initially homogeneous (Borg, et al., 1959). The stress-strain pattern of mechanical deformation induces certain crystallographic elements of which twinning planes are the most common among feldspars. Such mechanical twinning in plagioclase has drawn particular attention of many investigators, as is seen from a review paper of the Norsk Feldspar Volume (Norsk Geologisk Tidsskrift, Bd. 42; 1962) and also in the recent papers of Vogel (1964), Vogel and Siefert (1965), Laves (1965) and Tobi (1965). These papers deal with mechanical twinning expanding it to cover all plagioclases at all temperatures. According to Suwa (1956) deformation of a fully grown crystal is considered to be least effective in forming pla-
gioclase twins. The mechanical stresses induce twinning in feldspars in the initial stages; in other words mechanical twinning is induced only up to a certain degree of imposed stresses, but beyond that, continued stresses give rise to exactly the opposite or "retrograde" effect; that is to say, that the author believes that the deformation caused by continually imposed mechanical stresses may be effective in effacing the twinning. Rapidly applied stress below the shattering point will create the most intimate twinning with numerous, narrow lamellae but on continued action of stresses the feldspars show a tendency of elimination of twinning. That is, the rearrangement and re-organisation of the deformed grains, such as intragranular lattice displacement, grain rotation, ionic migration by diffusion or solution which take place without destroying the cohesion of the grain, constitute the internal mechanism of the elimination of twinning and thus the final untwinned feldspar is believed to be the form attained in response to continually applied external forces. Because, the microfabric which results from deformation of a certain kind will obviously be affected by recrystallisation of the constituent minerals and hence, it might be thought that such recrystallisation of post-deformation date-(post-tectonic crystallisation, pre-crystalline deformation)-would obliterate most of the microfabric and the effacing of twinning in feldspars is probably a consequence.

But the process of detwinning is observed in some feldspar grains, but not in all. It is well known, that resistance against plastic flow by translation gliding is different in different directions. In other words, along certain directions the crystals behave brittle, while in other directions, the same crystal may be highly plastic. The random orientation of the individual
feldspar grains provides that only some of the grains are oriented with their glide lines and glide planes parallel to the direction of shearing stress. Only such grains offer a minimum resistance against plastic flow. Some grains, which have their translation lines inclined to the direction of shearing stress yielding correspondingly greater resistance to flow. Such grains, which have their glide lines perpendicular to the shearing stress fail to yield by translation at all. Therefore, the unfavourably oriented crystals easily break by rupture and are shattered while the crystals which remain unshattered, still experiencing the stresses yielded by plastic deformation of which, the effacing of the twinning may be a final result. Probably, this explains why certain crystals suffered elimination of twinning while others do not. Unfortunately, our understanding of the mechanical behaviour of rocks, comes not from the most important rock-forming minerals like feldspars but is based on the indirect inferences from the theoretical and experimental knowledge achieved during the intense studies of metals and other easily yieldable crystalline substances.

Further twinning in feldspars is presumed to be one of the several imperfections, which have been referred to as irreversible or thermodynamically unstable imperfection. Pressure, temperature, composition and size alone are not the factors to contribute in imposing this imperfection, but is dependent also upon the history of the crystal. Therefore, feldspar twinning, which is thought to be irreversible imperfection, tends to disappear in course of time when the crystal experiences appreciable thermal mobility inside or when it is left to itself for sufficient period of time under mechanical stresses. Such induced mechanical twinn-
ing and its subsequent elimination will not be possible over short periods of time but will take place during periods which are sufficiently long to permit appreciable thermal mobility resulting probably in the migration of elements particularly of Si and Al. Such periods of time may vary in different members of the isomorphous mixtures of plagioclase series and also in potash feldspar variants.

Similarly, elimination of twinning in quartz has been recorded by Bailey et al (1958). From an X-ray study, they observed that the Dauphine twinning which is one of the commonest types of twinning in quartz, is found to be absent in the deformed quartz, which is believed to be related to the process causing asterism and polygonisation. The other common type of quartz twinning according to Brazil law is not revealed by X-ray study.

From this study, it may be stated that elimination of twinning in feldspars is a post-tectonic deformational feature.

Comments on the Elimination of Plagioclase Twinning:

TOM, F.W., BARTH:

"A twin is thermodynamically unstable and should in the course of time convert into a single crystal. If a twin is formed, either primary or secondary, the thermal energy will be too low to eliminate the twinning immediately. Once formed it takes, therefore, some external energy, for instance, mechanical energy or stress to eliminate the twin structure.

Another way of looking at a twin is in term of disorder. At high temperature, the thermal vibration in the crystal lattice
results in disorder, a minor kind of disorder in twinning which, therefore, can be regarded as transitional between high temperature disorder and low temperature order".

HANS RAMBERG:

"The conclusion is that the twinning in feldspar is (often) eliminated by a process of recrystallisation and/or annealing of mechanically deformed feldspar grains. The fact that twinning is much less abundant in regional metamorphic rocks than in lavas and other magmatic rocks supports your view. I think that time and rate of recrystallisation is very significant. The slowness of metamorphic recrystallisation favours untwinned grain to form".

O.F. TUTTLE:

Professor Tuttle expresses that it might be possible to investigate the detwinning of plagioclase experimentally.

R.C. EMMONS:

"My own thinking is that there is more than one cause of twinning as you suggest and that if we can fully order plagioclase we can eliminate order–disorder twinning. I am now attempting to do this by hydrothermal treatment".

FELIX CHAYES:

"Where materials are of a sort in which imperfections, dislocations, etc., can be observed directly or their consequences can be subjected to thorough, even if indirect, test as in metals, for instance, their study has been remarkably useful, both practically and theoretically. To date, however, the common rock forming minerals have proved almost completely resistant to this approach."
The suggestion of Emmons about the relation of twinning to zoning may certainly be wrong - I rather suspect it is - but it is at least a scientific hypothesis in the ordinary sense; that is to say, in principle at least, it is subject to test. With the advent of the electron probe, this test now becomes a practical possibility".

THOMAS DONELLY:

"Very few American geologists take seriously the observations of Emmons and Mann on twinning and zoning, except to agree that such zoning is indeed eliminated by the same phenomenon that induces twinning. However, they are not mutually exclusive. It is also well known, that the ultimate degree of deformation of a twinnable crystal is indeed an untwinned crystal. It is well-known, for example, that precipitation of impurities on twin composition faces may lock these faces and effectively prevent further migration of the twin boundary during continued stress. The current consensus is that virtually all of the elimination of twinning is the result of recrystallisation".

IRIS BORG:

(1) There is no evidence that twinning in plagioclase can be eliminated by annealing; we have annealed a whole series of plagioclases at 900°C. upto 20 days with no detectable diminution.

(2) It is conceivable that mechanical twinning carried to completion might result in an apparently "untwinned" grain, but only those twin laws associated with mechanical twinning might be involved. (albite and perhaps pericline).
(3) There is good reason to suppose that only certain plagioclases can be induced the twin mechanically. The current thought is that twinning can only occur in a disordered lattice (High temperature plagioclases); thus failure to see twinning in low grade metamorphics may be related to their low temperature (ordered) structural state.

(4) There is no reason to suppose that most twinning observed is anything but a growth phenomenon. Under ideal laboratory conditions, a very large differential stress is needed to induce mechanical twins. "Untwining", involving slip in the direction opposite to that producing the twins, has never been observed to occur in the laboratory."

—oo00oo.