JOINT PATTERN AND DYKE TRENDS IN THE TIRUPATI AREA, ANDHRA PRADESH, INDIA

by K. V. SURYANARAYANA, *Reader, Department of Geology,*
Sri Venkateswara University, Tirupati, A. P.

and

K. ANJANAPPA, *Lecturer, Department of Geology, Indian Co-operation*
Mission, Kathmandu, Nepal

(*Received 26 April 1974; after revision 28 January 1975*)

An attempt is made to give a genetic interpretation to the fracture systems that prevail in the granite bodies in the Tirupati area. The dykes in the area represent tension fractures trending almost east-west. On either side of the tension fractures, at an angular distance of 23°, are the shear joints, described as Set II and Set III, that constitute a conjugate set. There are also other conjugate sets of low angle. The interpretation is drawn that the fracture systems in this area are a result of the compressive stress that acted in the E-W direction superposed over the local stress system generated by the rising granite body. The opinion is also offered that the fracture systems of this area are of the nature of bending fractures formed by contraction of a cooling igneous body. The tectonic episode that ensued did not alter the prevailing stress condition in the area. Evidences for repeated periods of igneous activity and for the reopening of the fractures at different periods are provided by slickensided surfaces on joints, chloritisation of dykes by later dislocation, and palaeomagnetic data. Dykes of Tirupati conform in their trend to those occurring in other parts of Southern India; and from this a suggestion is made for an integrated analysis of the joints and dyke fractures together to assess their wider implications in the genetic interpretation of the granitic rocks of Southern India.

INTRODUCTION

Tirupati, the famous place of pilgrimage in Andhra Pradesh, India, remains geologically uninvestigated, except for the rocks of the Tirumalai hill range (as the northern portion of the Tirupati township is called) to which reference is made by King (1872) in his memoir on Cuddapah and Kurnool formations. The northern portion of Tirupati that constitutes the Tirumalai is covered by quartzites and shales of precambrian (proterozoic or purana of India) times, whereas to the south are found the granites and gneisses of Archaean era. The present paper deals with the structural geometry exhibited by the fracture system found in the granites of the Tirupati area that constitutes the hitherto unsurveyed southern part of the Tirumalai hill range. About 120 square miles of the area were surveyed for joint pattern and dyke trend. The map of the area is shown in Fig. 2. The location of the area in the Indian peninsula is shown in Fig. 1.

In the account that follows, the trends of the dykes have been compared with the trends of the joints in the granites. An attempt is made to correlate these two

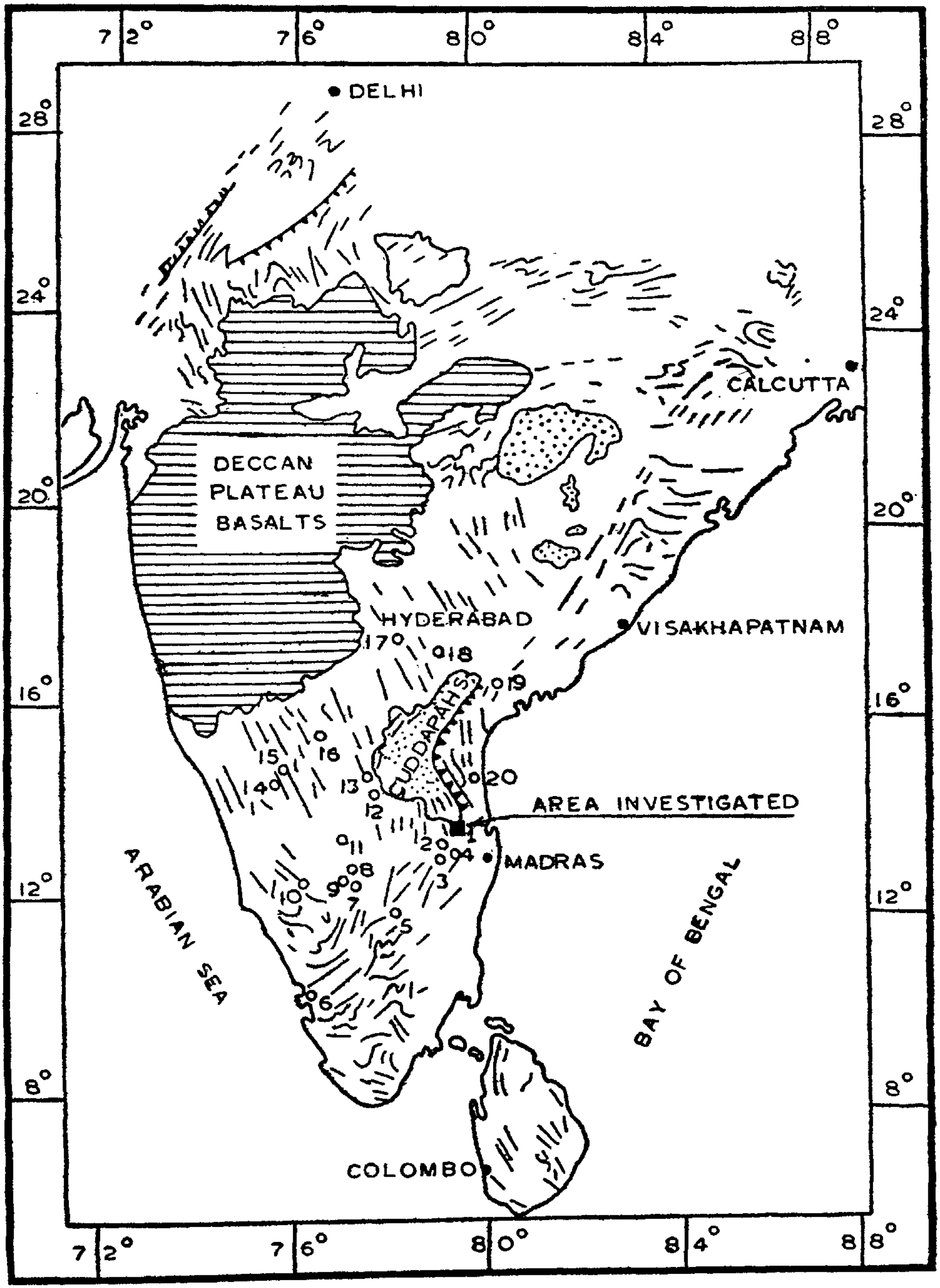

FIG. 1 The tectonic map of India showing the location of the area investigated. No. 1 is the Tirupati area investigated. Numbers 2 to 20 refer to areas from where dykes are reported by other workers. Trends of the dykes of these areas are given in Table I.

fracture systems by analysing them with the help of the strain elipsoid. It is also a well known fact that a close relationship exists between the fracture system and the movement of the block of rock in which fractures occur. A discussion on the rise and emplacement of the granite body is made by a study of the fracture patterns. A petrofabric diagram for the granite is also prepared to help in this correlation. Mechanics of intrusion of the dykes are also discussed.

DYKE TRENDS

The country rock which the basic dykes traverse in the Tirupati area is essentially coarse-grained, equigranular granite, with scarce gneissic foliation here and there, of Archaean age. The majority of the dykes of the area has a trend varying from E10°N to E10°S. These are considered here as east-west dykes. This is the most prominent trend as would be evident from the map (Fig. 2). There are other dykes of less frequency trending N60°W, and still others of much less frequency trending N70°E and N10°W. Dykes trending N10°W are regarded as N-S dykes for the purpose of description. The N-S dykes traverse the E-W dykes, and hence are younger than the latter. Dykes with N60°W, and N70°E trends often occur as off shoots and branches from the main E-W dykes. Most of the dykes are vertical, or near vertical, with a uniform width. Simple dykes predominate, but multiple and composite dykes were also encountered.

The abundance of E-W dykes may lead one to consider them to constitute a set or a system, of dykes. Parallel sets of dykes, reported from several parts of the World, such as, the well-known Tertiary dyke swarms of British isles described by Bailey and Wilson (1924) and Richey (1939), dyke swarms of the Canadian Shield described by Fahrig and Wanless (1963), meta dolerite dyke swarms from Bakersville —Roan mountain area described by Wilcox and Poldervaart (1958), and dyke swarms from Southern Beartooth mountains described by Printz (1964), to quote a few examples, are all those that fall under the category of dyke swarms. In the Tirupati area, the east-west dykes are all parallel and abundant, and hence constitute a linear dyke swarm.

As already pointed out, only an area of 120 sq. miles in Tirupati is examined for dyke distribution. The authors have made a comparison of the dyke trends of Tirupati area with the dyke trends occurring in the adjoining areas, and also with those occurring in many other parts of the Peninsula to make a wider correlation. Data collected are presented in Table I. The location of the areas is shown in Fig. 1.

It would be evident from the Table I that N-S, E-W and NW trends are the most prominent trends for the majority of the dykes of the Peninsula. This is not without significance and it must be due to the causes of a large order.

JOINT PATTERN

Well-defined, regular sets of joints traverse the granites of the area. Many of them occur in parrallel sets, with a straight course and definite trend. All joints were measured without any subjective preference to any one set. In this area, the subjective element is likely to loom large, because of the presence of the E-W dykes to which other fractures will be presumed to run parallel. Also, if several sets are

TABLE 1

Trends of the dolerite dykes in the Peninsular India

Area No.	Name of the area	Trends of the dykes	Source
1.	Tirupati	E—W, N—S	Present investigation
2.	Chittoor	E—W and NE	Natarajan (1965)
3.	Bommasamudram	E—W and NW	Jayakumar (1963)
4.	Sholingur	E—W and N—S	Janardan (1964)
5.	Salem	E—W and N—S	Pascoe (1950)
6.	Cochin	NW	,,
7.	Satanur	E—W and NNW	Devaraju and Sadasivaiah (1966)
8.	Closepet	E—W and NW	Suryanarayana (1960)
9.	Chanapatna	E—W and NNW	Kripanidhi (1968)
10.	Mysore	E—W and N—S	Pascoe (1950)
11.	Tumkur	NNW	,,
12.	Penukonda	E—W	,,
13.	Ramapuram	E—W and NW	Prasad (1966)*
14.	Chitaldrug	E—W and N—S	Pascoe (1950)
15.	Molakalmuru	E—W and NW	Naik and Sadasivaiah (1964–65)
16.	Bellary	E—W and NNW	Pascoe (1950)
17.	Hyderabad	E—W	,,
18.	Nalgonda	E—W and N—S	,,
19.	Guntur	NNW and ENE	,,
20.	Nellore	NNW and ENE	,,

present, one is likely to be impressed by the trend of one set, because of one's predilections. Hence, as a caution against this pitfall, the authors considered it desirable to avoid a selective study of any particular set. Almost every joint was measured and recorded, so as to make the selection completely representative. Mullar (as quoted by Pincus 1951) in recognising this problem of obtaining an impartial sample states that the best method is to measure all joints; and his statement is particularly noteworthy in the sampling of joints.

Another handicap encountered in taking joint readings is that some joints, especially the shear joints are associated with zones of closely-spaced fractures, i.e., fracture cleavage (Plate I, Fig. 1). The spacing of the fracture cleavage is so close in such cases that counting of every cleavage would boost up the frequency of joints. They were disregarded in the statistical analyses of the joints. In Plate I, Fig. 2, joints are spaced farther enough, such that each fracture can be considered to represent a joint.

Many joint sets were noticed, each set maintaining parallelism with one another. In several areas selected, each area is characterised by one particular set, the other sets being subordinate. Joints of each area are separately described. A total number

---

*Full details are available with the authors.

of 1,300 joint readings were taken. In order to portray the attitude of the joints and to ascertain the number of sets present, the poles of the perpendiculars to the joint planes were plotted on the lower hemisphere of the Schmidt's Equal Area net.

Area No. 1—For the area No. 1, near Chandragiri, the diagram (Fig. 2a) shows strong maxima at the north and south poles, with a pole concentration of 33 per cent, indicating the predominance of E-W joints with a dip of more than 80°. There are also E-W dykes in this area, and hence these joints may be classed under tension joints. The occurrence of E-W joints in this area is an exception, because they are negligible in the other parts surveyed. The minor maxima, along the circumference, indicate two other joint sets, one set having an average strike of N35°E, the other set having a strike of N10°W. The more or less continuous contour with a split in the northeastern and south-western ends indicates a number of other subordinate joints with diverse trends. The granite in which the E-W joints occur is coarse-grained.

Area No. 2—In the diagram (Fig. 2b) for area 2, near Perur, the maxima positions indicate two sets of joints, one with a strike of N45°E and the other N64°W. The joint set of N45°E trend is dominant, because the maximum for this set has a pole concentration of 30 per cent. The other set with N64°W trend is rather subdued and has a pole concentration of 18 per cent. These two sets of joints appear to form a conjugate set, as between them they make an angle of 71°, and also because other sets are totally absent. The major part of the diagram is blank indicating the absence of other sets. It is significant to note that there are no dykes in this area and the rock type in which the joints occur is gneissic in character.

Area No. 3—In the diagram (Fig. 2c) for area No. 3 near Rayalacheruvu, the maximum with a pole concentration of 30 per cent gives an average strike of N64°W for one joint set. The spread of the contours from the eastern and western ends of the diameter to the south-western and south-eastern directions with maxima of 6 per cent and 11 per cent respectively, reveals the presence of another set of joints with a strike varying between N20°E and N15°W; for this the average strike may be taken as N-S. Compared with N64°W joint, the N-S joint set is subordinate, but is of equal significance owing to the absence of any other set next in importance to N64°W joint set.

Area No. 4—In the diagram (Fig. 2d) for area No. 4 near Ramapuram, there are a number of maxima along the circumference of projection, the highest maximum concentration being 10 per cent representing the joint set that trends N70°E. Other sets have N50°E, N27°E, and N-S trends having a pole concentration of 4 per cent, 7 per cent and 4 per cent respectively. All these sets give rise to a girdle around the circumference, but the girdle is interrupted at many points.

There are also minor maxima within the diagram indicating other sets of joints with low dips. They lie in the four quadrants of the diagram. The maxima of all these joints have a spread, suggesting a group of joints in each set with a slightly varying trend.

The maximum in the north eastern quadrant gives for one joint set a trend of N70°W with a low dip of 40° to the SW. This trend is constituted of a number of sub-sets with a trend varying from N70°W to N85°W. The maximum in the south-

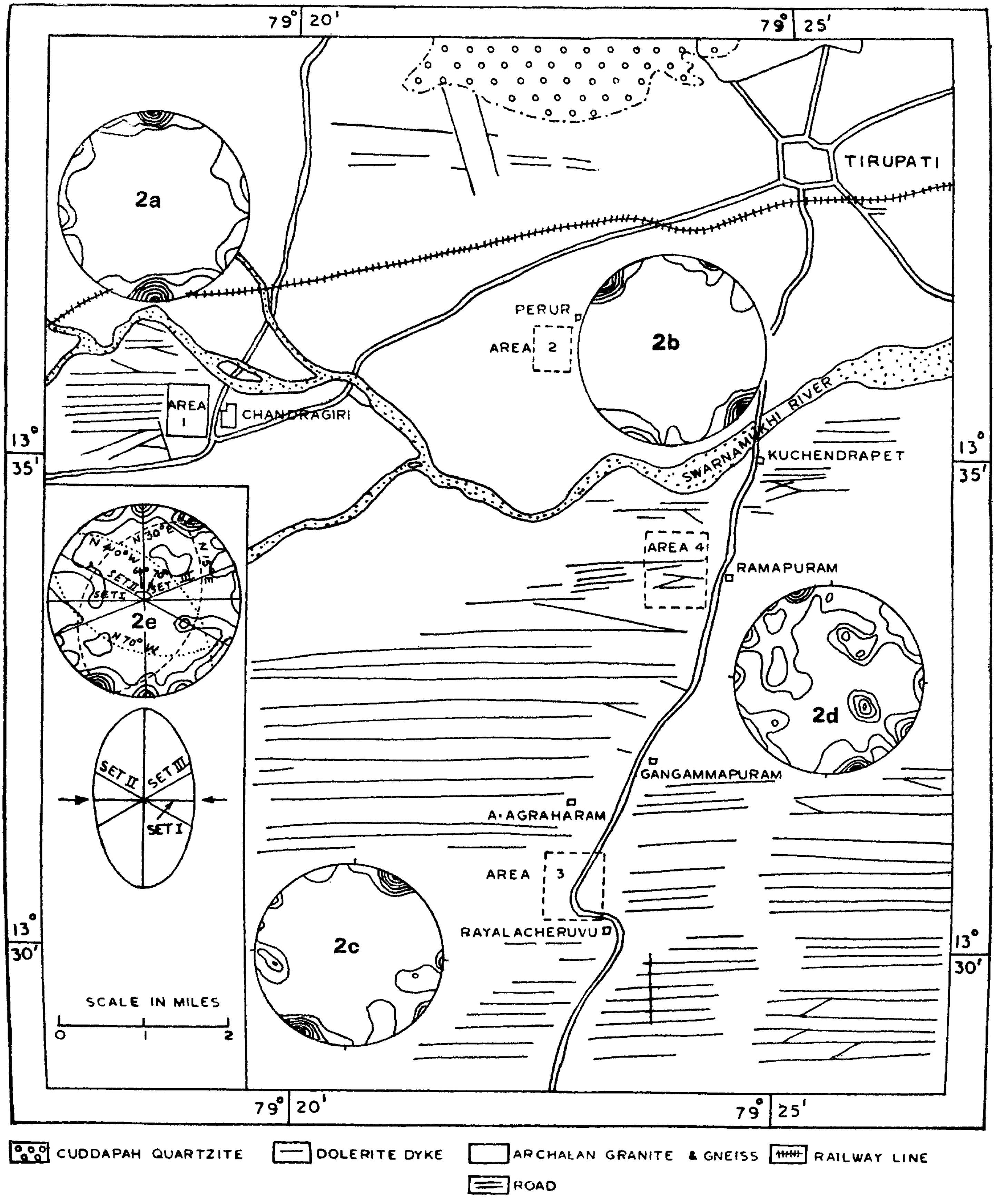

FIG. 2 a–e. Joint diagrams for the areas 1 to 4. a, Poles of 350 joint planes, contours in per cent 31–26–21–16–11–6–1 per 1% area ; b, Poles of 73 joint planes, contours in per cent 26–21–16–11–6–1 per 1% area ; c, Poles of 345 joint planes, contours in per cent 26–21–16–11–6–1 per 1% area ; d, Poles of 532 joint planes, contours in per cent 9–7–5–3–1 per 1% area.

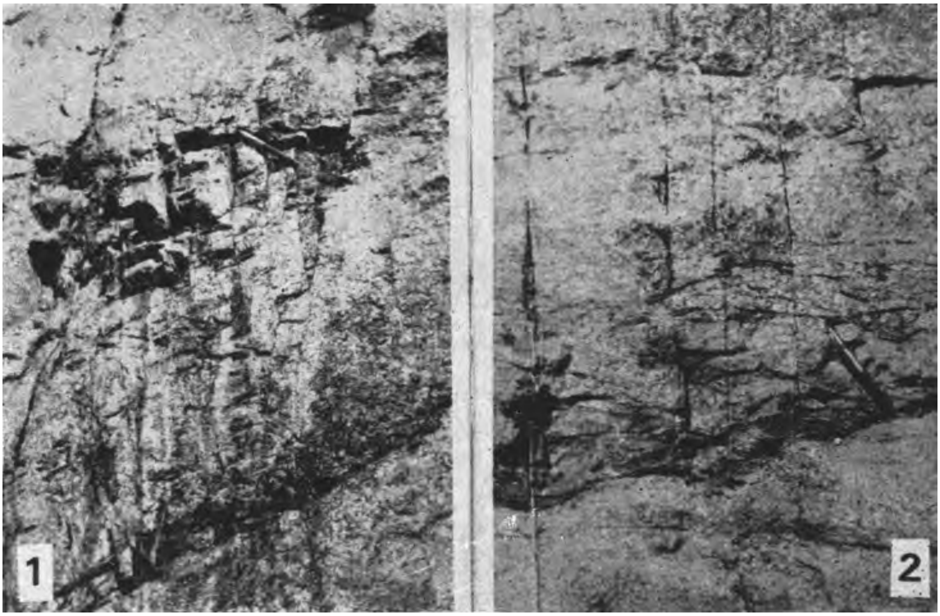

PLATE I

Figs. 1–2. 1, Photograph of fracture cleavage in granite near Ramapuram (refer map Fig. 2). 2, Photographs of joints spaced farther apart in granite exposures near Ramapuram.

western quadrant gives an average strike of N40°W for another set with a dip of 60° to the NE. These two sets, i.e., one with N70°W trend dipping SW at 40°, and the other with N40°W trend dipping NE at 60° form a conjugate shear with a dihedral angle of 80°.

The maxima in the north-western and south-eastern quadrants indicate another conjugate shear, one set having a trend of N10-25°E and another set with a trend of N30°E. The set with N10-25°E trend is subdued and has a greater spread, because of a number of subsets of which it is constituted. An average strike of N15°E dipping in general eastern direction at angles varying from 20 to 45° is shown for this set. The set with N30°E trend has an average dip of 40° in the NW direction. The dihedral angle between the two sets of this conjugate system is approximately 90°.

A look at the Figs. 2a—2d for the four areas reveals that one particular set of joints is characteristic of one area, and the other in another. As a rule, in nature, one seldom finds all joints in the same outcrop. When joints of all outcrops are combined in one area, we are opt to find a girdle pattern. This aspect has been specially recognised by De Sitter (1964).

Fig. 2e is the composite diagram of the poles of joints of the areas 1 to 4. More or less a girdle pattern is evident revealing the fact that joints with diverse trends are possible under the same stress condition. If the stress direction is the same for the whole area under investigation, the paucity of all sets in one area, or the existence of one particular set in an area, must be due to differences in lithology of the rocks

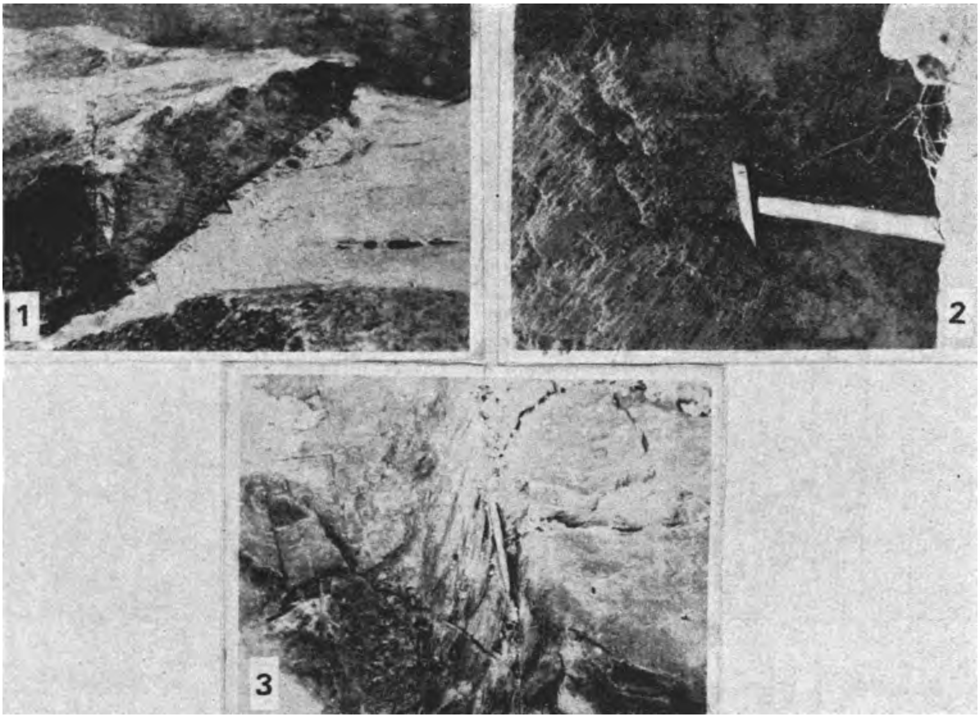

PLATE II

FIGS. 1–3. 1, Photograph of a vertical surface of a joint plane at Rayalacheruvu showing slickensides. The striations have a plunge of 50°. 2, A close-up view of the slickenside, showing markedly developed striations and interspersed steps. 3, Photograph of the fault plane in dolerite. The dolerite has been converted into chlorite schist. The plane of schistosity is diagonal to the trend of the fault (The pen length is along the trend of the fault).

and also to the local stress differences generated in an area subjected to a stress of a large order. Chapman and Wingard (1958), in discussing the age of the dykes in Maine Coastal region, lay stress on the physical properties of the rocks and state that susceptibility of a rock to fracture should depend on its lithology, texture, and structure. De Sitter (1964) and Firman (1960) also state that the joint system is very much dependent on the lithological characters of the rocks. In the granitic massif of the Tirupati area, there are exposures, here and there, of gneisses and patches of migmatites. Joint frequency in the gneisses is very much less. The migmatitic zones are devoid of joints. The rocks also differ in the degree of their coarseness. These structural differences in Tirupati area must be reckoned as factors for the predominance of one set of fractures in each area. The E-W joint set (set I) which is absent in all areas except in area 1, finds a place in the composite diagram with 7 per cent pole concentration. The most prominent set revealed in the composite diagram is the set II with N64°W trend which has a pole concentration of 10 per cent. This receives contribution from N64°W joint set of areas 2 and 3. This other prominent one is set III, trending N70°E, which has a pole concentration of 5 per cent receiving contribution from areas 2 and 4. Incidentally, set II and III constitute a conjugate shear with a small dihedral angle of 46°. However, neither set II nor set III is present in a single exposure. One set occurs in one area with the exclusion of the other. This fact can also be explained in terms of the observations made by Beloussov (1962) who states that one system or another of the shear fractures develops more intensely because of the nature of horizontal compression (Beloussov 1962, p. 597). The N-S joints constitute the IV set with only 3 per cent concentration receiving contribution from the areas 1, 3, and 4. The conjugate sets found in area 4 are also respresented in the composite diagram. They are subordinate and their origin is discussed separately (Fig. 3).

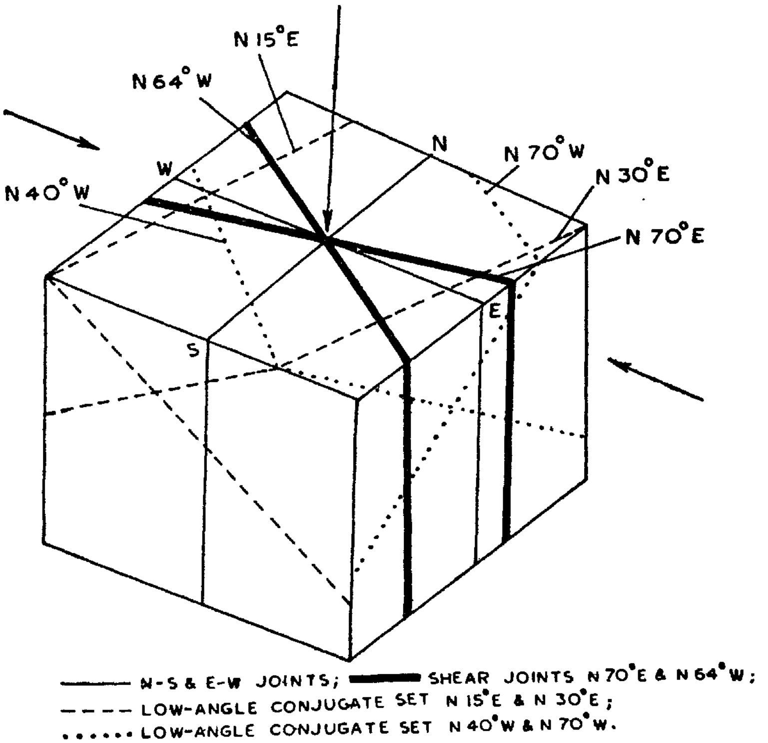

FIG. 3. Block diagram showing the major joint sets of the composite diagram of Fig. 2e.

EVIDENCE OF MOVEMENT ALONG JOINT PLANES

Slickensides were noticed at several places along the shear joints indicating displacement (Plate II, Figs. 1 and 2). So, many of the shear joints are also faults. The planes of shear have a thin veneer of quartzitic material which is dark, glassy, like a tachylite. Microsections revealed a black, glassy groundmass with crushed grains of quartz sprinkled all over.

The striations in the slickenslides are generally horizontal indicating that the shears are strike-slip faults. Cases were also noticed where the striations are diagonal to the strike and dip of the joints suggesting movement of the blocks in an oblique direction. Beloussov (p. 597) points out that displacement in the exact direction of strike and dip are extremely rare and states that in nature one commonly finds displacements of intermediate type. One case of shear joint with striations in the intermediate direction was noticed in the southern part of the area. The shear planes strike N30°E with vertical dip. The striations of the slickensided surface plunge N30°E at 50°. Here about half a dozen shear joints occur so closely spaced, only a few inches apart, that blocks of rocks can be removed along the shear joints into thin slabs. Both the fault surfaces of the slab have slickensides with interspersed ridges presenting an irrefutable proof of fault movement. The disposition of the blocks, the direction of fault movement, and the orientation of the slickensides are shown diagrammatically in Fig. 4a. Fig. 4b is a projection of the three blocks on a horizontal plane 'XY'. Arrows in the figure indicate the direction of movement of the

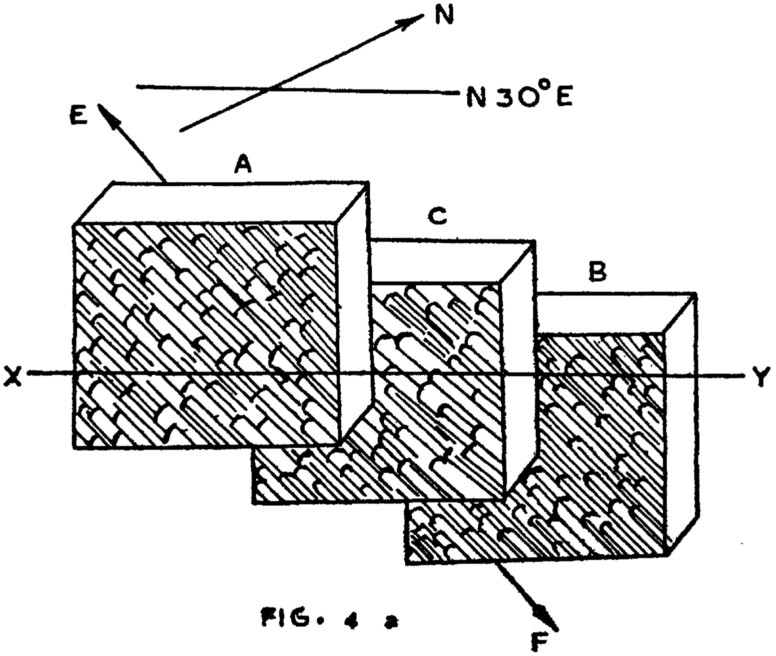

FIG. 4 a

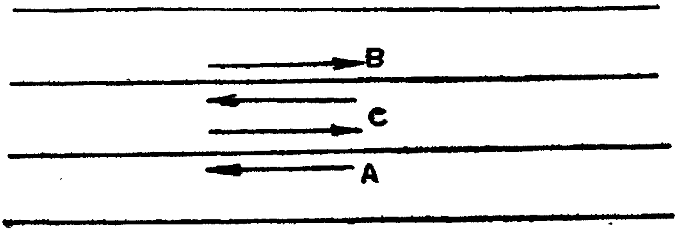

FIG 4 b

Fig. 4 a–b. a, Diagrammatic representation of slickensided surfaces. E = direction of movement of block A. F = direction of movement of block B. EF also indicates the direction of striations. b, Projection of the three blocks of Fig. 4a on a horizontal plane XY with the arrows indicating the direction of movement.

blocks. In the differential movement undergone, block 'C' may be regarded as remaining stationary. Badgley (1965, page 133) states that slickensides on joints are indications of compressional origin. In the following pages the view is expressed that in Tirupati compressional forces have acted in the E-W direction.

The evidence of movement along joint planes is of some significance, becuase such movements have taken place along dyke fractures also to cause metamorphic effect on dolerites. Four such dykes were noticed with fault planes running in the middle of the dyke parallel to the length of the latter. One such dolerite dyke was noticed about 4 miles south of Tirupati, a photograph of which is shown in Plate II, Fig. 3. Along the fault plane the dolerite is converted to chlorite schist. The faults are of the nature of strike-slip faults.

Petrofabric analysis of the granite was carried out to obtain further evidence of movement of the granite body during or after its final solidification. One oriented specimen of granite was collected from the area number 1. The petrofabric work is handicaped by the following limitation :

1. The coarse-grained nature of the rock which greatly restricts the number of quartz grains in a section.

2. Absence of any other mesoscopic element, like foliation, lineation, slaty cleavage etc., and the resultant difficulty of fixing the co-ordinate axis a, b, and c.

The specimen was collected with reference to geographic co-ordinates from a vertical E-W joint surface facing north. The section was cut perpendicular to north. Optic axes of quartz were plotted on the lower hemisphere of an equal-area-net adopting the usual Universal Stage technique.

Fig. 5 is the orientation diagram of 225 quartz axes of this even textured, megascopically isotropic granite. The maxima lie on the circumference, the girdle is lacking, and the unfilled part runs irrationally in the diagram. The plane of projection

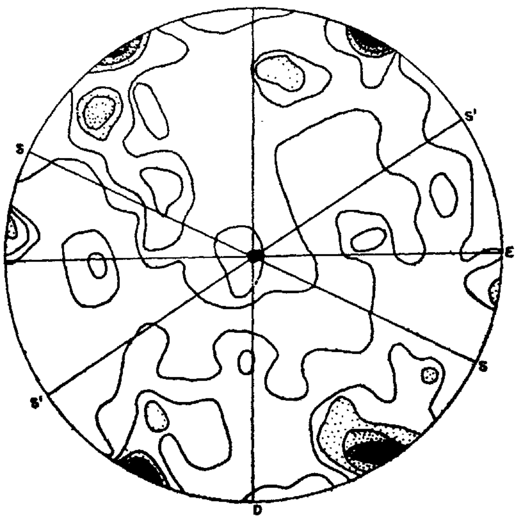

FIG. 5. Orientation diagram of 225 quartz axes, contours in per cent 4–3–2–1–½ per 1 per cent area.

of the diagram is also the vertical face parallel to the E-W joint, as the section is cut perpendicular to north. The maxima would suggest that the quartz axes tend to be oriented in the E-W joint plane. The resemblance of the petrofabric diagram to near orthorhombic symmetry is also evident. The angle between the maxima is 60°. Down direction lies along the diametre that, more or less, bisects the acute angle between the two maxima. Statistical S- planes, SS and S′ S′ are drawn, to which the maxima may be said to be polar. The two shear planes would than present an acute angle to the E-W diameter suggesting the operation of the greatest compression in the E-W direction. A valid inference from this mesoscopic and microscopic fabric study would therefore emerge, which is that the compressive stress that has acted in the E-W direction has not only produced mesoscopic shear joints II and III (Figs. 2e and 3) that intersect in a vertical axis perpendicular to the surface of the earth, but also the statistical conjugate shears SS and S′ S′, that intersect in a horizontal axis parallel to the N-S direction. This near orthorhombic fabric clearly indicates the anisotropy created by plastic deformation when the magma had not completely solidified.

ORIGIN OF THE FRACTURE SYSTEMS

With this general picture of the sets of joints present in individual areas, and the sets of joints that reveal themselves in the composite diagram, the possible mechanism of their formation will now be discussed.

The most widely quoted work on the origin of joint sets and dyke fractures is that of E. M. Anderson (1951). He draws the relationship between the joint pattern and stress directions. Three principal stress directions are supposed to be present over a broad area. The magnitude of the three principal stresses PQR, may be considered to be $P>Q>R$. The greatest and least stress are horizontal and the medium stress Q is vertical . In such a situation, shearing planes, either faults or joints, may develop in planes parallel to the median stress direction and making an acute angle bisected by the largest stress direction, whereas tension joints will be oriented parallel to this largest stress and perpendicular to the smallest stress. This view is also stressed by De Sitter (1959) and Billings (1968).

Application of this theory to the joint systems and dyke trends of the Tirupati area would suggest that the E-W dykes occupy the tension fractures, formed as a result of the greatest stress acting in the E-W direction and the least stress N-S. The compressive force has acted in the E-W direction is confirmed by the trend of the gneissic foliation in the area which is N-S. The tectonic map of India (Fig. 1) also shows N-S trend for the gneisses of the area. The greatest horizontal stress acting in the E-W direction might, in the course of time, decrease, leading to an increase of the minimum principal stress acting in the N-S direction. This corresponds to the tensile stress produced by an elastic release of the compression in the E-W direction as explained by De Sitter (1964). The horizontal stress parallel to the dyke would then become smaller. In that case, the condition would get reversed and tension fractures may form oriented N-S to be filled up by magmas to form N-S dykes. The N-S dykes of the Tirupati area may have this origin, indicating that they are later than the E-W dykes. It should however, be recorded here that, at some places, N-S dykes are seen cutting across E-W dykes. There are E-W and N-S joints represented in the composite diagram as set I and set IV respectively. These may be regarded as tension joints parallel to the two dyke sets formed by a similar cause as outlined above.

The maximum stress that has acted in this E–W direction to cause tension fractures with the same orientation must also generate conjugate shears that would present an acute angle to the greatest principal stress direction. The axis of the greatest principal stress is shown by the arrows in the strain ellipsoid in the inset, Fig. 2. Such shear joints are present in this area, as revealed in the composite diagram where they are shown as set II and III. Set II trends N64°W and set III N70°E. The dihederal angle between the two, which is 46°, is nearly bisected by the axis of the maximum stress which is E–W, or, to be more exact, the maximum stress may be shown to act in N85°W–S85°E direction. This is also the trend of the dykes regarded as filled-up tension fractures. Badgley (1965, p. 101) has summarised the views of host of workers on the magnitude of the dihederal angle, and states that this angle is generally 60°. De Sitter (1959) states that the angle varies from 15° to 90°. This variation, according to De Sitter, is due to the differences in the rock properties, or to the weight of the overburden. Anderson (1951) points out that the shear joints make an angle varying from 15° to 45° with the largest principal stress. Several other workers like Parker, Spencer, and Muehlberger (quoted by Badgley 1965, p. 101) have noted paired joints which have a dihederal angle between 0° and 20°. The angle 46° between set II and III for conjugate shears in Tirupati falls within the limits set from theoretical and experimental considerations. The low dihederal angle for the Tirupati shear fractures may also be due to the internal friction which reduces the angle to less than 60° (Badgley 1965, p. 106), though differences in rock properties may also be another cause.

The above findings reveal the essential features of the joint pattern in the Tirupati area and should not be taken to mean that other orientations are subordinate, or are unimportant. The girdle along the circumference in the composite diagram (Fig. 2e) with minor maxima indicates other sets of subordinate fractures suggesting either a more complicated mechanism, or the intervention of any other additional factor, as the cause for the development of fracture systems in the rocks of this area. The additional factor that the authors consider likely to have played a part in this area is the local stress system generated by the uprise of the granite body itself. A thin solid crust appears to have formed, the interior being still liquid. Continued upword movement subjected the consolidated crust to tension causing ruptures. The formation of ruptures in this way is very well explained by Cloos (Balk 1937). These ruptures must have had orientations in all directions. Igneous intrusions precede, accompany, or follow crustal movements. The E–W compressive stress has arisen out of this crustal movements. This compressive force has emphasised, and even augmented the frequency of the E–W tension fractures and of the conjugate N64°W, N70°E shear fractures, relegating the other fracture systems to a subordinate position. At the final stages of development of the granite body, the settling process ensued. This settling process is similar to the collapse of the crust due to the release of compressive stress. The result of this would be the formation low-angle joints or flat normal faults. The joint set striking N15°E dipping east at angles varying from 20° to 45° and another set striking N30°E and dipping westerly at an angle of 40° (Fig. 2e) would constitute low angle conjugate shear with a dihedral angle of roughly 90°. This angle is bisected by the compressive stress acting in the vertical direction (Fig. 3). This vertical stress has a moderate increase so as to produce an angle of 90° for the conjugate set. The vertical stress coincides more or less with the centre of the diagram.

The other low angle conjugate shear has one set striking N70°W, dipping S W at an angle of 40°, the other set strikes N40°W, dipping N E at 60° (Fig. 2e). These may also be taken as normal faults. The acute angle between the two is 80° which has the bisectrix in the vertical direction (Fig. 3). This points to the maximum stress acting vertically down-wards as a result of the gravitative settling of the crust. This vertical stress coincides more or less with the centre of the diagram, as in the other conjugate system mentioned above.

It is now made clear that the two conjugate shear joints of low-angle with a common bisectrix in a vertical direction present evidence of gravitative settling of the granite crust. A little deeper analysis of the conjugate system of joints would strengthen the view expressed earlier on the operation of elastic release of the E–W compressive force. If we disregard the dip of these conjugate sets and consider only their strike, there will be one conjugate system with an average strike of N23°E and another with an average strike of N55°W (Table II). The angle between the two adds upto 78°. The two systems thus present an acute angle to the increasing compressive force acting in the N–S direction. Fig. 3 is a block diagram wherein are shown the major joint sets of the composite diagram (Fig. 2e). In Table II, the main joint sets described are summarised with their trend, dip, and angle of intersection.

The analyses so far made may have to be reviewed in the light of observations made by Beloussov (1962) for there are no other evidences to confirm that the low-angle joints are normal faults. Beloussov (1962, p. 578) refers to the tension joints as bending fractures formed by the internal tensions due to contraction caused by cooling. The development of bending fractures also depends upon the intensity of bending, the overall ambient pressure, and the physical property of the rock. These circumstances produce tension fractures that may involve the entire area and form general jointing. Beloussov further argues that contraction joints cannot always be distinguished from tension fractures of tectonic origin since they are produced by the same kind of stress; and hence states that direct tectonic action as the cause of fracturing in the intrusives is usually exaggerated. The tectonic forces do not directly produce fractures, but they affect the orientation of the contractoin fractures which orient themselves in accordance with the anisotropy created when the magma was not still solidified.

There is ample justification to apply Beloussov's idea to the fracture pattern in Tirupati. It has already been discussed that a local stress system is created by the rising granite body. The pattern of orientation of joints, as revealed in the composite diagram, would suggest the granite of the Tirupati area to be an intrusive body. All the joints produced in the granite are tension joints of a general kind formed by contraction due to cooling. The orientation of these joints depends upon the anisotropy produced during the plastic deformation of the granite body which had still not completely solidified. This anisotropy is revealed by no other fabric feature than the

TABLE II

Major joint systems of the Tirupati Area

	Tension joints		High-angle conjugate shear		Low-angle conjugate shear			
	Set I	Set IV	Set II	Set III	Conjugate system V		Conjugate system VI	
Trend	E—W	N—S	N64°W	N70°E	N40°W	N70°W	N15°E	N30°E
Dip	70°—90°	76—90°	75—90°	72—90°	60°NE	40°SW	20°—45°E	40°NW
Angle of intersection	90°		46°		80°		90°	
Maximum stress direction	E—W		E—W		Vertical		Vertical	
Average strike	—		—		*Average strike of system V N55°W		Average strike of system VI N23°E*	

*Angle between the two strike directions is 78°.

petrofabric diagram (Fig. 5). The intrusive body has later undergone tectonic deformation after complete solidification. During this tectonic episode, the compressive stress acted in the E–W direction, and it is likely that this compression has developed certain fractures of tectonic origin, like the conjugate shears (set II and III), affected the orientation of the contraction fractures formed during the stage of cooling and solidification of the magma, and reopened the old ones. The low-angle conjugate shears may actually be the thrust faults formed during the rise of the granite body. The E–W tension joints, which are now filled up by the dykes, present geological data to indicate that they are repeatedly reopened by the E–W compressive forces. Multiple and composite E–W dykes have been noticed by the authors (Anjanappa & Suryanarayana 1971, and unpublished thesis of Anjanappa) to suggest that the cracks were repeatedly reopened as a result of several consecutive movements in which each opening has been followed by a new intrusion of magma. Additional evidences for repeated movement is presented by the chloritization of the E–W dykes. by faulting along their strike. The movement is of strike-slip type lending support to the operation of the E–W compressive stress in the area. Another evidence is provided by the slickensided surfaces. Badgley (1965, p. 128) quotes the work of Harrison and Moench in this regard and reports several periods of jointing in the precambrian rocks of the Central City—Idaho, Springs area, Colorado. According to him the oldest joints are of primary granite tectonics and are related to the principal precambrian intrusive episodes. Folding followed, or acccompanied, each period of precambrian intrusion. He recognises two periods of folding associated with jointing. It is to be noted, therefore, that repeated periods of tectonic episodes are not uncommon in the geological history of the precambrian terrains subsequent to intrusion. It is appropriate in this connection to refer to the palaeomagnetic data obtained by the authors (Anjanappa & Suryanarayana 1971) on the dykes of this area, for the data suggest the different ages for the dykes. From the evidence of a multiple dyke, which strikes E–W, where the younger intrusive is found to be reversely magnetized and the older normally magnetized, many E–W dykes were examined for their magnetic directions; and from this study it was found that the E–W dykes fall into two classes viz., those that are normally magnetized and the others that are reversely magnetized, indicating two different ages for the E–W dykes. There are other E–W dykes that are metamorphosed to green schists (metadolerites) showing scattered magnetic directions; they are the oldest dykes. The N–S dykes of the area are the youngest, as they cut across the E–W dykes. The N–S dykes show consistent magnetic direction, the azimuth being 278°, which is different from all the others. They are correlated with the baked Cuddapah shales of Precambrian age. It should, therefore, be noted that the dykes of Tirupati have formed in four different periods occuppying the old rejuvinated joints and filling up those formed anew. The story may be the same for all the joint patterns.

CONCLUSION

The joint systems and the dyke trends together present evidence of a compressive stress acting in an E–W direction. These have caused the development of E–W tension joints, set I, and the shear joints, set II & III. Increase of the minimum principal stress in the N–S direction, or the elastic release of the compression in the E–W direction, has led to the development of another set of tension fracture, set IV, oriented

N–S. The N–S tension fractures are, therefore, of later formation. The two tension fractures have been filled up by basic dykes. The N–S dykes are also younger than the E–W dykes, as borne out by the fact that the N–S dykes traverse the E–W dykes at several places. The subordinate low-angle conjugate sets of joints are formed as a result of a local stress system developed by the intrusion of a granite magma, or due to the gravitative settling of the granite crust. The trend of the low-angle joints may also be due to the increase of compressive stress in the N–S direction. The low angle conjugate joints with their bisectrices, in a vertical direction, coinciding with the centre of the diagram (Fig. 3) present evidence to the collapse of the granite crust by gravity. That the low angle conjugate shears may actually be thrust faults formed during the rise of the granite body is also not ruled out, as evidence for normal faulting is lacking. All the joints of the area are the result of contraction due to the cooling of an intrusive body cannot also be completely ruled out. If only one were to apply Beloussov's analysis, they were primarily tension joints of a general kind formed by contraction, and were repeatedly reopened by later tectonic episodes. This is amply corraborated by the slickensides along the joint planes, chloritization of dykes along strike-slip faults, and palaeomagnetic studies of the dykes.

A close correlation has been established between the dyke fracture and the other joint systems in the area from a geometric and genetic point of view. They are all assumed to have formed under the same stress system. An intrusive episode followed by a tectonic episode is envisaged. Comparison of the dyke trends of the Tirupati area with those occurring in the other parts of the peninsula has brought out the fact that the dyke trends in all the areas are, more or less, the same. It, therefore, appears reasonable to assume that the uniform trend exhibited by all these dykes must be due to the same cause as the one ascribed to the Tirupati area, but of a larger order. Were we to subcribe to the view that the intrusives episode, and the later tectonic episode superposed on the former, develop the same kind of stress, then it becomes necessary to make an integrated study of the dyke trends with the locally developed joints in every area, wherever intrusive granites and other similar rock types, like charnockites, exist. The Southern part of the Indian peninsula is essentially composed of granites, gneisses, and charnockites of Archaean age. Joint patterns in all these rocks in relation to the dyke trends must be studied in order to make an extended interpretation worthwhile. In view of the recently increasingly developing tendency to regard all granite bodies as products of granitization, the study of the fracture systems in all the areas, which is utterly lacking in the geological literature of India, becomes a desideratum to establish an intrusive origin for these rocks, as is now done for the rocks of the Tirupati region.

ACKNOWLEDGEMENT

The authors offer their thanks to Prof. M. G. Chakrapani, Head of the Department of Geology, Sri Venkateswara University, Tirupati, for the facilities offered to carry out the work in the field and in the laboratory.

REFERENCES

Anderson, E. M. (1951). *The Dynamics of faulting and dyke formation.* 2nd Edn., Oliver & Boyd, Edinburgh, pp. 7–21.

Anjanappa, K. (1971). The dolerite dykes of the Tirupati area, Chittoor District, Andhra Pradesh, India. Ph. D., Thesis, S. V. University, Tirupati (*Unpublished*).

Anjanappa, K., and Suryanarayana, K. V. (1971). Palaeomagnetism and the phenomenon of multiple intrusion. *Curr. Sci.*, **40**, 15, 406–407.

Badgley, P. C. (1965). *Structural and tectonic principles.* Harper & Row, pp. 101–133.

Bailey and Wilson (1924). Tertiary and post-Tertiary geology of Mull Loch Aline & Oban. *Mem. geol. Surv.*, p . 360.

Balk, R. (1937). Structural behaviour of igneous rocks. *Mem. geol. Soc. Am.*, 5.

Beloussov, V. V. (1962). *Basic problems in geotechniques.* McGraw Hill Book Co. Inc., pp. 578–597.

Billings, M. P. (1968). *Structural Geology.* Prentice-Hall, Inc., p. 95.

Chapman, C. A., and Wingard, P. S. (1958). Physical control and age of dyke formation in the Maine coastal region. *Bull. geol. Soc. Am.*, **69**, p. 1193.

De Sitter (1964). *Structural Geology.* McGraw Hill Book Company, pp. 99–118.

Devaraju, T. C., and Sadashiviah, M. S. (1966). Dolerite dykes of Satnur, Halaguru area, Mysore State. *J. Karnatak Univ. Sci.*, **XI**, p. 89.

Fahrig, W. H., and Wanless, R. K. (1963). Age and significance of diabase dyke swarms of the Canadian Shield. *Nature*, **200**, p. 934.

Firman, R. J. (1960). The relationship between joints and fault patterns in the Eskdale Granite (Cumberland) and the adjacent Borrowdale volcanic series. *Q. J. geol. Soc. London*, **116**, pp..317–348.

Janardhan, A. S. (1964), Dyke rocks of Sholingur, North Arcot District, Madras State. *Ind. Min.*, **5**, p. 117.

Jayakumar, D. (1963). Igneous and Metamorphic Complex of Bommasamudram, Chittoor district, Andhra Pradesh. Ph. D. Thesis of the Madras University (*Unpublished*).

King, W. (1872). Kadapah and Kurnool formations in the Madras Presidency. *Mem. geol. Surv. India*, No. 8.

Kripanidhi, A. (1968). The Peninsular gneiss and the associated rocks of Channapatna area, Bangalore District, Mysore State, India. Ph.D., Thesis, S. V. University, Tirupati (*Unpublished*)

Naik, M. S., and Sadashiviah, M. S. (1965). Dyke rocks of Molakalmuru area, Mysore State. *J. Karnatak Univ.*, **10**, p. 67.

Natarajan, R. (1965). Geology of the area in the neighbourhood of Chittoor, Andhra Pradesh, India. Ph. D. Thesis of the Madras University, Madras (*Unpublished*).

Pascoe, E. H. (1950). *A manual of the Geology of India and Burma.* Publication of the Govt. of India, New Delhi.

Pincus, H. J. (1951). Statistical method applied to the study of rock fractures. *Bull. geol. Soc. Am.*, **62**, p. 81.

Printz, M. (1964). Geological evolution of the Beartooth Mountains, Montana & Wyoming. Pt. 5, Mafic dyke swarms of the Southern Beartooth mountains. *Bull. geol. Soc. Am.*, **75**, p. 1217.

Richey, J. E. (1939). The dykes of Scotland. *Trans. Edinb. geol. Soc.*, **13**, p. 393.

Suryanarayana, K. V. (1960). The Closepet granites and the associated rocks. *Ind. Min.*, **1**, 86–100.

Wilcox, R. E., and Poldervaart, A. (1958). Meta dolerite dyke swarm in Bakersville—Roan, Mountain area, North Carolina. *Bull. geol. Soc. Am.*, **69**, p. 1323.