TWINNING IN CORDIERITE

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ABSTRACT

The various possible types and patterns of twinning in cordierite are discussed, based partly on a study of cordierites from seven different Indian localities. The simple, polysynthetic (parallel and interpenetrating), and cyclic (radial, stellate and concentric) twins are distinguished and their interrelationship discussed.

Twinning is exclusively confined to the (110) and (130) faces, the former being much more common and important. Polysynthetic twinning appears to be the most common type in coarse grained rocks but large scale interpenetration of lamellae is rare. Lamellae twinned on similar planes are either parallel or make angles of 60° whereas lamellae twinned on unlike faces are inclined to each other at angles of 30° or 90°. The various possible features in interpenetrating lamellae and the nature of curved and irregular composition planes are also explained. Simple and quick methods of determining the identity of the twin planes are outlined.

It is suggested that complex twin patterns (stellate, concentric etc.) are generally confined to cordierites formed at high temperatures whereas simpler types are characteristic of cordierites formed at lower temperatures.

INTRODUCTION

Polysynthetic and cyclic or sector twinning in cordierite has been known for a long time and it has also been recognized that (110) and (130) form the most important twin planes. Lasaulx (1884), Hussak (1883), Eskola (1914), and Dittler and Kohler (1938) are among those who have referred to twinning in cordierite in some detail; but descriptions of the different types of twinning and the identity of the twin planes are not common in contemporary petrographic literature in English. An attempt is made in this paper to present a morphological study of the different types of twinning in cordierite and their inter-relationship.

Cordierite crystallizes in the orthorhombic system, and the axial elements given by Dana (1914) are: 0.5871:1:0.5585, which give the interfacial angles *mm'''* i.e. $(110)\wedge(1\bar{1}0)$ as 60°50′ and *dd'* i.e. $(130)\wedge(\bar{1}30)$ as 59°10′. These interfacial angles approximate 60° which explains the pseudohexagonal twinning in cordierite. The axes of optic elasticity, X, Y and Z coincide respectively with the crystallographic axes *c*, *a* and *b*. All the angles between the twin planes and the Y and Z directions are 30° or 60°.

MATERIAL

Cordierite-bearing rocks from fourteen widely separated Indian localities were examined. Specimens from seven localities had cordierite show-

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ing little or no twinning and the material from the other seven localities was studied in some detail. Several thin sections were cut from each of the specimens available and studied with the help of the Universal stage. Nearly all the twinned grains in each section and not less than a hundred grains per specimen were examined.

Details of the material studied are given in Table 1:

TABLE 1

No.	Name of rock	Locality	No. of specimens examined	2V of Cordierite	Descriptive notes
1	Cordierite rock	Kiranur, Trichinopoly, Madras	Several	(−) 62°–82°	Cordierite is coarse grained, anhedral and non-pleochroic in thin sections. Inclusions of sillimanite and zircon noticed; pinitization limited.
2	Hypersthene-biotite-sillimanite-cordierite rock	Paderu, Vizag, Madras	2	(+) 64°–82°	Coarse anhedral grains of cordierite showing feeble dichroism; swarms of pleochroic haloes present; pinitization advanced. See Walker and Collins (1907).
3	Hypersthene-garnet-cordierite-biotite rock	Polavaram, West Godavari, Madras	1	(−) 78°–85°	Sillimanite and spinel also present; kelyphitic borders round spinel and intergrowths of codierite with hypersthene and quartz often seen.
4	Hypersthene-biotite-cordierite rock	Ganguvarpatti, Madura, Madras	2	(+) & (−) 60°–84°	Cordierite sometimes weakly pleochroic, pinitized along borders; positive and negative grains in the same section noticed.
5	Cordierite gneiss	Tadenpatti, Ramnad, Madras	5	(+) 68°–86°	Quartz, plagioclase, biotite, hypersthene and garnet also present. Cordierite is feebly pleochroic; pinitization very negligible.
6	Cordierite-garnet-biotite-sillimanite rock	Kadamballi, Bangalore, Mysore	1	(+) 72°–82°	Abundant pleochroic haloes, moderate pinitization and no recognizable pleochroism.
7	Enstatite-cordierite vitrophyre and cordierite-labradorite vitrophyre	Gobindpur, Bokaro coalfield, Bihar	3	(−) 68°–75°	Octahedra of magnetite abundant. Euhedral and subhedral grains of cordierite show complicated twinning. Sometimes strongly pleochroic. See Fermor (1924) and Venkatesh (1952).

CLASSIFICATION AND DESCRIPTION OF TWINNING

Twinning is exclusively confined to the (110) and (130) planes. The twinning and composition planes are identical as the twin axis can be considered to lie normal to the composition plane and hence both the terms are used synonymously. The various possible twin patterns could be classified as shown below:—

(1) Simple
(110) or (130)

- Polysynthetic or lamellar
  - (2) Parallel lamellae
  - Interpenetrating lamellae; inclined to one another
    - at
      - (3) 30° twinned on both (110) and (130)
      - (4) 60° Twinned on either (110) or (130) only
      - (5) 90° Twinned on both (110) and (130)
- Cyclic or Sector
  - Radial
    - (6) Trilling
    - (7) Sixling
    - (8) Twelve-sector twin ("twelveling")
  - Stellate
    - (9) Six-pointed star
    - (10) Twelve-pointed star
  - Concentric
    - (11) Triangular
    - (12) Hexagonal:
      - (*a*) parallel
      - (*b*) with 30° tilt
    - (13) Six-pointed star:
      - (*a*) pointing to corners
      - (*b*) pointing to the sides
    - (14) Twelve-sided or "dodecagonal"
    - (15) Twelve-pointed star

The twin types Nos. 9, 11, 13, 14 and 15 have not been observed during this study and do not seem to have been described in the literature. A short description of these various twin types is given below:

(1) *Simple twinning:* The crystal is made up of two individuals separated by a single composition plane. Twinning could be either on the (110) or (130) plane. The vibration directions Y and Z make angles of 60° and 30° respectively, with the trace of the (110) composition plane in a basal section, and 30° and 60°, respectively with the trace of a (130) composition plane. The X vibration direction or the *c* crystal axis coincides in both individuals and lies parallel to the line of intersection of the (110) and (130) planes. Hence, only the positions of two vibration directions, viz. Y and Z need be established. The twin axis which is per-

pendicular to the *c* axis lies very nearly in the (110) plane if it is twinned on (130) and *vice versa.*

Simple twinning is seen in all the rocks except No. 7, but simple twins with (130) as the composition plane are exceedingly rare. The simple twins are, however, scarce as compared to polysynthetic twins and tend to occur where untwinned grains are abundant.

Repetition and modification of this simple type give rise to the following other types.

(2) *Polysynthetic or multiple twinning:* The twinning here is repeated at close intervals giving rise to two sets of lamellae as typified by plagioclase felspars. The following two subclasses are easily recognized under this: (*a*) When the twin planes are all parallel to one another, it can be called "parallel repetition" (*b*) When the twin planes form two or more parallel sets inclined to one another, it can be described as interpenetration or interdigitation twinning (Figs. 2 & 3). The twin lamellae may intercept one another at angles of 30°, 60° or 90°.

When two sets of inclined lamellae intersect at 60°, the normal to the composition plane of each set of lamellae would coincide with the Z vibration direction of the other set of lamellae if both are twinned on (110) (Fig. 5), and with Y direction if both are twinned on (130). If the twinning is on both (110) and (130) and the angle of intersection is 30°, the normals to the (110) and (130) would coincide with Z and Y respectively, of the other set of intersecting lamellae.

Polysynthetic twinning producing either parallel or interdigitated lamellae is the most common type of twinning among the rocks studied. It is particularly well developed in specimens 2, 3, 4 and 5. Parallel lamellae are much more common than the prominently interdigitated type.

(3) *Cyclic or sector twinning:* The composition planes in this type of pseudohexagonal twinning radiate from a central point at intervals of 30°, 60° or 120°. Three different classes of twin patterns are recognizable under this.

(*a*) Radial twinning: In the simplest case where there are only three twin planes making mutual angles of 120°, trillings are formed; six twin planes radiating from the centre at 60° to one another result in a sixling (Rosenbusch, 1905. Figs. 53 to 55). The twin planes could possibly be either (110) or (130) but only the former has been observed. Both these are produced by like twin planes and not by a combination of unlike twin planes. The basal section of the sixling would show the Y vibration direction to be radial if twinned on (130) or Z direction radial if twinned on (110). In the case of a trilling the above relations would be reversed.

In another modification there are twelve sectors ("twelveling"), four of

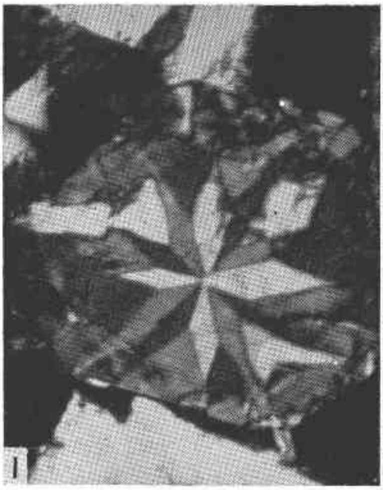

Fig. 1. Stellate twin. ×100.

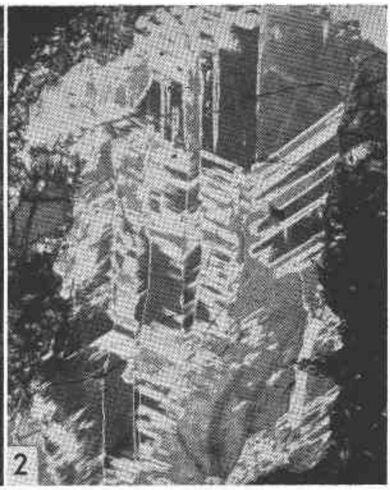

Fig. 2. Interpenetrating lamellae. ×40.

Fig. 3. Interpenetrating lamellae. ×31.

Fig. 4. Concentric twin. ×49.

Figs. 1 to 4. Photomicrographs of cordierite (all under crossed nicols).

which form a set having identical optical orientation, *i.e.* every third sector is optically similar. This type of pattern is built by a combination of both (110) and (130) twin planes in alternating arrangement. Dittler and Kohler (1938) and Rosenbusch (1905) have recorded indentical forms.

(*b*) Stellate twinning: A more picturesque form of cyclic twinning is the star-shaped pattern. It may be a six-pointed star formed by six rhombs pointing towards the hexagonal sides. This pattern can be built only by similar twin planes and is a modification of the sixling. In the twelve-pointed stellate twin (Fig. 1) there are twelve radiating twin planes which bifurcate towards the periphery and join up with adjacent ones (Venkatesh, 1952*a*).

(*c*) Concentric twinning: A concentric twin pattern results when polysynthetic twin lamellae lie parallel to or at angles of 30° or 60° to the

FIGS. 5 to 8 are diagrammatic representations of twin patterns projected on the basal plane. The slow vibration direction is represented either by arrows or by shading. Optically identical twin units are given same numbers (1, 2 or 3).

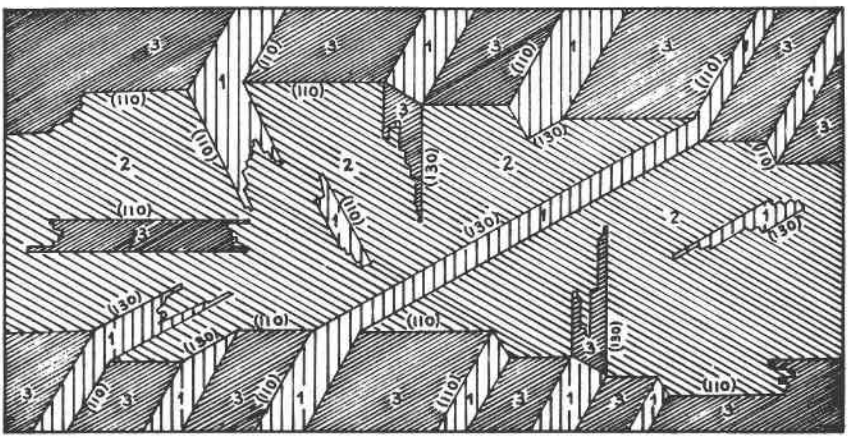

FIG. 5. Relation of interpenetrating lamellae twinned on (110).

hexagonal outline (Fig. 4). The concentric arrangement can only be superimposed on a radial twin of which it is a further modification. Since polysynthetic lamellae may be arranged parallel or at 30°, 60° or 90° to the two enclosing twin planes in each sector, it is evident that a large variety of concentric twin patterns are theoretically possible; but only a few types have been observed.

A trilling may give rise to a concentric hexagonal pattern which is parallel to the outer periphery. In this case all the twin planes are similar and inclined to one another at angles of 60° (Fig. 6). A triangular concentric pattern is also theoretically possible. Concentric patterns in the sixling may take the form of a hexagon or a six-pointed star. In the former case the concentric hexagonal pattern would look as though it has been rotated by 30° with respect to the hexagonal boundary. The six points of the star-shaped concentric pattern may point either towards the hexagonal corners (Fig. 7) or the sides.

In a twelve-sector twin, the secondary lamellae would form a twelve-pointed star (on the lines of a sixling) or a "dodecagonal" concentric pattern. A hexagonal concentric pattern could also be produced when the secondary twin planes branch off at 90° from the alternate radial twin planes which are normal to the sides of the hexagon. Diverse combinations of the radial, stellate and concentric types yield sometimes a very complex pattern (Fig. 8).

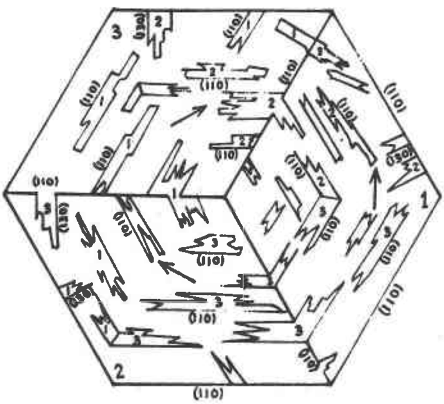

Fig. 6. Concentric hexagonal pattern on a trilling.

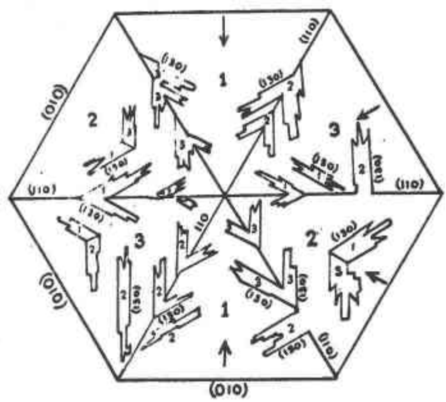

Fig. 7. Star-shaped concentric pattern on a sixling.

Cyclic twinning is confined only to specimen No. 7. Simple trillings and sixlings are rare even in specimen No. 7, whereas the "twelveling" and the twelve-pointed stellate twin are very common. Of the concentric types mentioned above, hexagonal pattern on a twelve-sector twin and a similar pattern modifying a trilling are the only forms observed. In all these the major twin planes pointing towards the outer hexagonal corners are (110), and (130) has never been found in this position.

Interpenetrating Twin Lamellae

The following features are seen when two sets of lamellae interpenetrate:

(*a*) When two sets of lamellae enclosed in a common host, cross each other at angles of 30° (*i.e.* twinned on dissimilar planes) or 60° (*i.e.* twinned on similar planes), the following possibilities have been noticed (Fig. 5): (1) One of the lamellae could be cut off against the other, in which case the plane of termination will have to be parallel to either of the vibration directions of the common host. Consequently, the composition plane that truncates the lamella, deviates by 30° or 60° from its original course. (2) But if a lamella is to maintain its optical identity after entering the new surroundings of the second lamella, it has to deviate by 30° or 60° from its course so as to be parallel to either of the vibration directions of the common host. (3) In case a lamella deviates in its

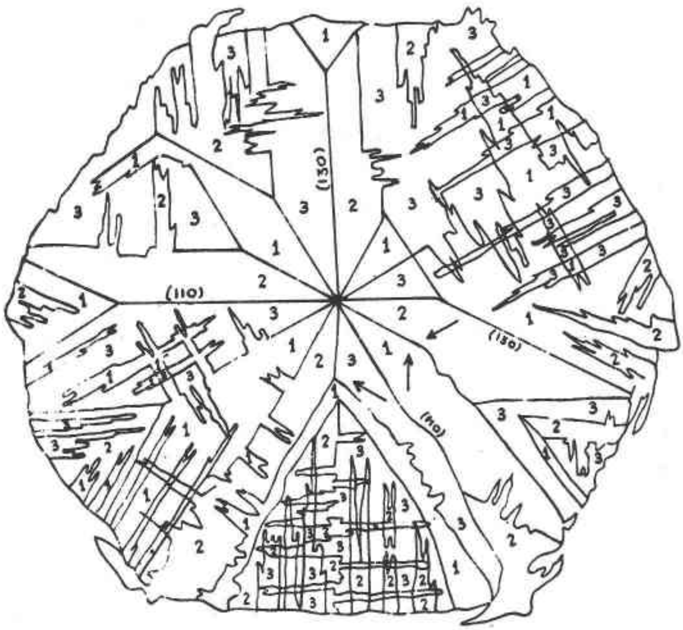

FIG. 8. Complex pattern due to a combination of different types of twinning.

course so as to be normal to the composition plane of a second lamella (in which it is enclosed), its identity would become similar to that of the common host.

(*b*) When two sets of lamellae enclosed in a common host and twinned on dissimilar planes interpenetrate at 90°, the resulting features are different, as both sets of lamellae have identical optical orientation and only two optically distinct units are present unlike three in the former case. Hence, if the lamellae cross one another, the area of overlap may show the same optical orientation as the common host or be identical with that of the lamellae.

Although in the thin sections examined the interpenetration of lamellae has not been encountered on such a large and prominent scale as to produce a general chequered pattern, minor and limited occurrences of all these variations are convincingly displayed (Fig. 2).

Determination of the Twin Plane

The identity of a twin plane could be established with the help of the Universal stage by plotting the X, Y and Z directions and the pole of the twin plane. The trace of the twin plane passes through the X direction; and the angular relations between the poles of the twin planes and the Y and Z directions of the twin individuals, reveal the identity of the twin plane. In simple twins the normal to a (110) twin plane would lie at 30° to the Y vibration direction of the two individuals, and if (130) is the plane, its pole would make similar angles with Z. When two or more similar or dissimilar twin planes are present, the pole of a (110) twin plane would coincide with a Z vibration direction whereas the pole of a (130) twin plane would coincide with a Y vibration direction.

The simplest and most rapid procedure for determining a twin plane in cordierite is as follows. The composition plane is turned north-south and made vertical so that the normal to the plane will coincide with the outer east-west axis of the Universal stage. The microscope stage is then turned to the 45° position and the outer east-west axis is rotated through 50° on either side of the 0° position to find out if the grain shows any extinction. The two individuals would show simultaneous extinction if they are twinned on (110), but if twinned on (130), they would only show equal change in birefringence but not total extinction. This is explained by the fact that the vibration directions do not make angles of 45° with the (130) plane (they make angles of $<30°$ or $>60°$) in any section normal to this plane. But in the case of the (110) plane the vibration directions at some stage make angles of 45° with the trace of the twin plane.

When two or more sets of lamellae inclined to one another are present, the section could be so tilted as to make both sets of planes vertical and sharp. The angular relations of Y and Z with the trace of the twin planes would establish their identity.

Without the Universal stage, identification of twin planes would be difficult unless sections are obtained roughly parallel to the base. But when two sets of inclined lamellae with nearly vertical composition planes are present, the procedure becomes simple. In cases where only one of the two sets of composition planes is sharp, it could be identified by finding whether a fast or slow direction coincides with its normal. Finally, if any twinned grain shows sharp composition planes and roughly symmetrical extinction exceeding 30°, the plane could be readily identified as a (110) plane; but if this extinction is 30° or less, it is of no help in identifying the twin plane.

General Conclusions

Twinning in cordierite seems to be confined exclusively to (110) and (130) planes, and no other twin laws were noticed during the study. Simple twinning and polysynthetic parallel twinning are almost confined to the (110) twin plane. Polysynthetic twinning producing two sets of lamellae inclined at 60° are very common and are all twinned on (110) but never on (130). Combination of (110) and (130) twin planes in prominent interdigitation twins have not been noticed. Lamellar twinning (parallel and interpenetrating) on (110) is by far the most common type of twinning observed. The (110) twin law is exceedingly more common and important than the (130) law. Eskola (1914) has commented on the minor role of the (130) twin plane in cordierite and considers that it is no twin plane at all and strictly not even a composition plane. But this is contradicted by the presence of alternating (130) planes in the "twelveling." It also forms distinct though small and less frequent lamellae.

All the twin planes of similar identity in a twin are either parallel or inclined to one another at angles of 60° or 120° (even multiples of 30°), whereas dissimilar twin planes make angles of 30° or 90° (odd multiples of 30°).

Any twin lamella can make any number of deviations at 90° to its immediate course and still maintain its identity provided it is in the same optical environment. This is also true of any composition plane. In such cases the composition planes oscillate between (110) and (130) at every turn. Repeated deviations of this nature on a submicroscopic scale would explain the bulging and thinning of lamellae and the curved and irregular nature of the twin planes so often seen.

The type of twinning found in cordierite seems to bear some relation to the nature of the rock in which it occurs. It is noteworthy that simple and polysynthetic twinning are the most common types in coarse to medium grained, gneissic or granular rocks where larger grains of cordierite generally occur. Some examples of sixlings and trillings in cordierites from gneisses, pegmatites, etc. have been recorded in the literature but no instances were found in the rocks studied. Cyclic twinning producing the complex radial and concentric patterns, are totally unrepresented in the rocks mentioned above and have been observed only in specimen No. 7 (vitrophyre) and similar petrographic types formed under comparable conditions (Hussak, 1883 and Venkatesh, 1952*b*). The synthetic cordierite crystals from melts studied by Shand (1943), Dittler and Kohler (1938), and Richardson and Rigby (1949) are described as showing highly complex twin patterns and idiomorphic outlines. The common presence of simple cyclic twins and sometimes complex modifications of it in some hornfelses and other pyrometamorphic rocks, has been repeatedly recorded in the literature.

It appears, therefore, that cyclic twins and the many complex modifications of it are common in, and characteristic of, cordierites which have formed under conditions of high temperature or from melts. On the other hand, cordierites from granular or coarse-textured rocks which have not been subjected to such high temperatures during their growth history, seldom show the complicated forms, but show sometimes the simple sector twins and most commonly the simple and polysynthetic types of twinning. Gorai (1951) has recorded similar evidence regarding the influence of temperature on the type of twinning in the case of felspars.

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References

1. Dana, E. S. (1914), A System of Mineralogy, p. 419.
2. Dittler, von E., and Kohler, A. (1938), Neue Beitrage zur Cordieritsynthese: *Zentral. für Min.*, etc. *Abt. A*, 149–159.
3. Eskola, P. (1914), On the petrology of the Orijarvi region in Southwestern Finland: *Bull. Comm. Geol. Finlande*, **40**, 173–174.
4. Fermor, L. L. (1921), In discussion on Tilley's paper: *Q.J.G.S.*, **80**, 70–71.
5. Gorai, M. (1951), Petrological studies on plagioclase twins: *Am. Mineral.*, **36**, 884–901.
6. Hussak, von E. (1883), Über den cordierit, etc.: *Sitsung. Akad. Wiss. Wien., Math. Nat.*, **87**, 332–360.
7. Lasaulx, von A. (1884), Über cordieritzwillinge in einem Auswurfling des Lacher Sees: *Zeits Krist.*, **8**, 76–80.
8. Richardson, H. M., and Rigby, G. R. (1949), The occurrence of iron-cordierite in blast furnace linings; *Mineral. Mag.*, **28**, 547–556.
9. Rosenbusch, H. (1905), Mikroskopische Physiographie, etc., 163–168.
10. Shand, S. J. (1943), Notes on cordierite, etc. *Am. Mineral.*, **27**, 391–395.
11. Venkatesh, V. (1952*a*), Stellate twinning in cordierite: *Curr. Sci.*, **21**, 183–184.
12. Venkatesh, V. (1952*b*), Development and growth of cordierite in para-lavas: *Am. Mineral.*, **37**, 831–848.
13. Walker, T. L., and Collins, W. H. (1907), Petrological study of some rocks from the Hill Tracts, etc.: *Rec. Geol. Surv. Ind.*, **36**, 1–22.

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