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Inclusion patterns in zoned garnets from Magerϕy, north Norway

T. B. ANDERSEN

Geologisk Institutt Avd. A., 5014 University of Bergen, Norway

ABSTRACT. Garnet porphyroblasts in metasediments from Magerøy crystallized during static metamorphism. They display three optical zones, each having characteristic inclusions and chemistry. The compositional zoning is related to prograde metamorphism (an inner zone, 1, and a graphite-bearing zone) and retrogression (the outer zone, 2). Inclusions of two types are present in zone 1: type 1 are equidimensional remnants of the matrix, preferentially included along planes of rapid growth; type 2 are tubular and represent recrystallized quartz grains concentrated along defects in the garnet lattice. The defects are lineage boundaries between growth segments related to screw dislocations on crystal faces. Crystal growth developed at relatively high degrees of supersaturation, but below the supersaturation required for the development of dendrites. The inclusions suggest rapid growth of zone 1, caused by heat flow from an adjacent interkinematic mafic/ultramafic intrusive complex. The graphite-bearing zone crystallized at the metamorphic peak, while the inclusion-free idioblastic rim probably developed during retrograde metamorphism.

GARNETS from Magerøy display similar chemical zonation to that documented in a number of recent papers. In addition, they are optically zoned and contain a complex pattern of inclusions.

Chemical zoning in garnet porphyroblasts has been extensively studied and the fractionation-depletion model suggested by Harte and Henley (1966), furthered by Hollister (1966), is widely accepted. Alternative and additional models to explain the common bell-shaped chemical profiles as well as irregular patterns have, however, been suggested, involving continuous and discontinuous reactions and diffusion (Anderson and Buckley, 1973; Tracy *et al.*, 1976; Yardley, 1977).

Several authors have utilized the geometry of inclusions in metamorphic minerals for elucidating the conditions under which porphyroblasts nucleated and grew. Garnets have received particular attention and their inclusion geometries, especially those developed during syn-tectonic growth, have been described in detail by several authors (Powell, 1966; Powell and Treagus, 1970; Schoneveld, 1977). The study of chemical zoning in relation to textural zones, characterized by certain inclusion geometries, has been recognized to be of particular importance in the understanding of the metamorphic conditions and tectonic regimes which existed during garnet growth (MacQueen and Powell, 1977; Olimpio and Anderson, 1978; Finlay and Kerr, 1979). The development of sector inclusions of the chiastolite type are common in some metamorphic minerals (Harker, 1939). In non-cubic minerals sector inclusions can be associated with sector zoning (Hollister and Bence, 1967). Such zoning is, however, not uniquely associated with sector inclusions, and develops when the rate of growth exceeds the rate of diffusion perpendicular to the growth layers (Hollister, 1970). In the case of rhombododecahedral garnet all the faces belong to the {110} form, and this may be reflected in the regular arrangement of sector inclusions.

The garnets from Magerøy display inclusions which have been taken as an indication of twinning (Harker, 1939). Such twinning in garnet is normally referred to as dodecahedral, and is usually only observed in Ca-rich garnets which are sometimes anisotropic (Goldschmidt, 1911; Atherton and Brenchley, 1972; Lessing and Standish, 1973; Murad, 1976). In isotropic crystals such twinning is not directly observable in thin section. According to the suggested origin of these inclusions (see below), however, their presence does not directly imply that the host crystal is twinned.

Geological setting and sample description. The studied samples are from the Magerøy nappe, the uppermost tectonic unit in the Caledonides of Finnmark, northern Norway (Ramsay and Sturt, 1976; Andersen, 1981). The nappe was emplaced during D_1 of the Scandinavian phase of the Caledonian orogeny (Andersen *et al.*, 1982), and a Barrovian zonal sequence ranging from the biotite to the sillimanite zone was developed. This regional metamorphism reached its peak at the D_1-D_2 interkinematic period (Andersen, 1979). The regional metamorphic isograds imprinted on the argillaceous and calcareous sediments of Upper

Ordovician–Lower Silurian age are modified around a syntectonic mafic/ultramafic complex intruded at the time of the regional-metamorphic maximum (fig. 1). No detailed study of the contact metamorphic aureole has yet been carried out.

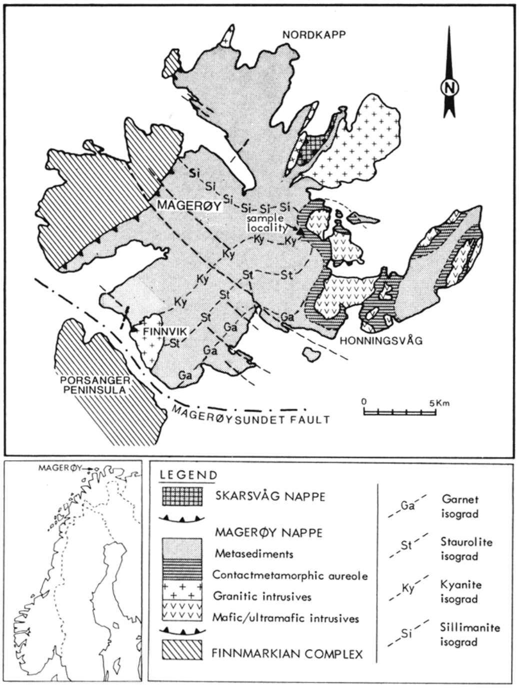

FIG. 1. Simplified geological and metamorphic map of Magerøy.

The configuration of the regional metamorphic zones developed during the interkinematic interval and the trend of the isograds (fig. 1) was only slightly modified by folding during D_2. Growth of syn-tectonic D_1 garnets were confined to the area north-west of the present (inter D_1–D_2) staurolite isograd (Andersen 1979). Everywhere within the north-western part of Magerøy, where garnets preserve inclusion fabrics, the cores of the porphyroblasts contain syn-tectonic inclusion patterns and the margins overgrow the S_1 schistosity (fig. 2).

The garnets described here were collected from an area which lies in direct continuation with the regional kyanite zone adjacent to one of the interkinematic mafic/ultramafic bodies of the Magerøy igneous complex. The mineralogy of the sampled locality is identical to that of the regional metamorphic paragenesis of the kyanite zone. Thin sections show biotite, garnet, staurolite, and kyanite to be major constituents together with quartz and plagioclase. Muscovite and opaques are accessories. A relic S_1 schistosity defined by the orientation of biotite is present, although strongly modified by recrystallization and neomineralization during the metamorphic maximum. The lack of syn-D_1 garnet at this locality indicates that the regional metamorphic grade was of low to intermediate greenschist facies during D_1. The *T*-conditions were, however, rapidly adjusted during the metamorphic maximum at the interkinematic period to equilibrate with that of the kyanite zone of western Magerøy. It is likely that this originated from the heat flow from the developing mafic/ultramafic complex which was intruded at this stage. In the studied samples idioblastic garnet and staurolite overgrow the early schistosity. The staurolite displays frequent penetration twinning. Kyanite nucleated after staurolite and overgrows staurolite and biotite, a textural relationship commonly observed also in western Magerøy.

Geometry of the inclusions. Inclusion geometries of two types are present in the garnets (fig. 2*a*). These are classified according to their orientation with respect to the crystallography of the garnet host.

Type 1 inclusions are concentrated along sectors which are parallel to the crystallographic planes of the host garnets defined as containing the line of intersection between two adjacent crystal faces and the centre of the garnets. Synoptically they form the sides of twelve pyramids with common apices at the centre of the garnet crystals, and bases formed by the $\{110\}$ crystal faces. The inclusion-rich planes represent the traces of the growing crystal edges (Harker 1939).

Where identification of the transparent inclusions is possible, either optically or by microprobe, they are found to consist of quartz. Fe–Ti oxides and graphite have been identified amongst the opaque inclusions, but these are usually to small to identify. The individual inclusions defining the type 1 pattern are dominantly equidimensional (fig. 2*b*). That the inclusions represent relics of the matrix is suggested by the gradual coarsening of the inclusions towards the margins of the garnets, an indication of prograde coarsening of the matrix. It is evident that a mechanism by which the matrix was preferentially trapped along growing crystal edges was operating. By a simple geometrical consideration it can be demonstrated that growth along crystal edges in a garnet with the form $\{110\}$ exceeds growth perpendicular to the crystal faces by a factor of 1.2. This is on the assumption that the crystal is a layerite and not a dendrite, and that the garnet retains its idioblastic habit.

The type 2 inclusions were also described by Harker (1939, fig. 100). They comprise slender tubular inclusions of quartz which are not relics of

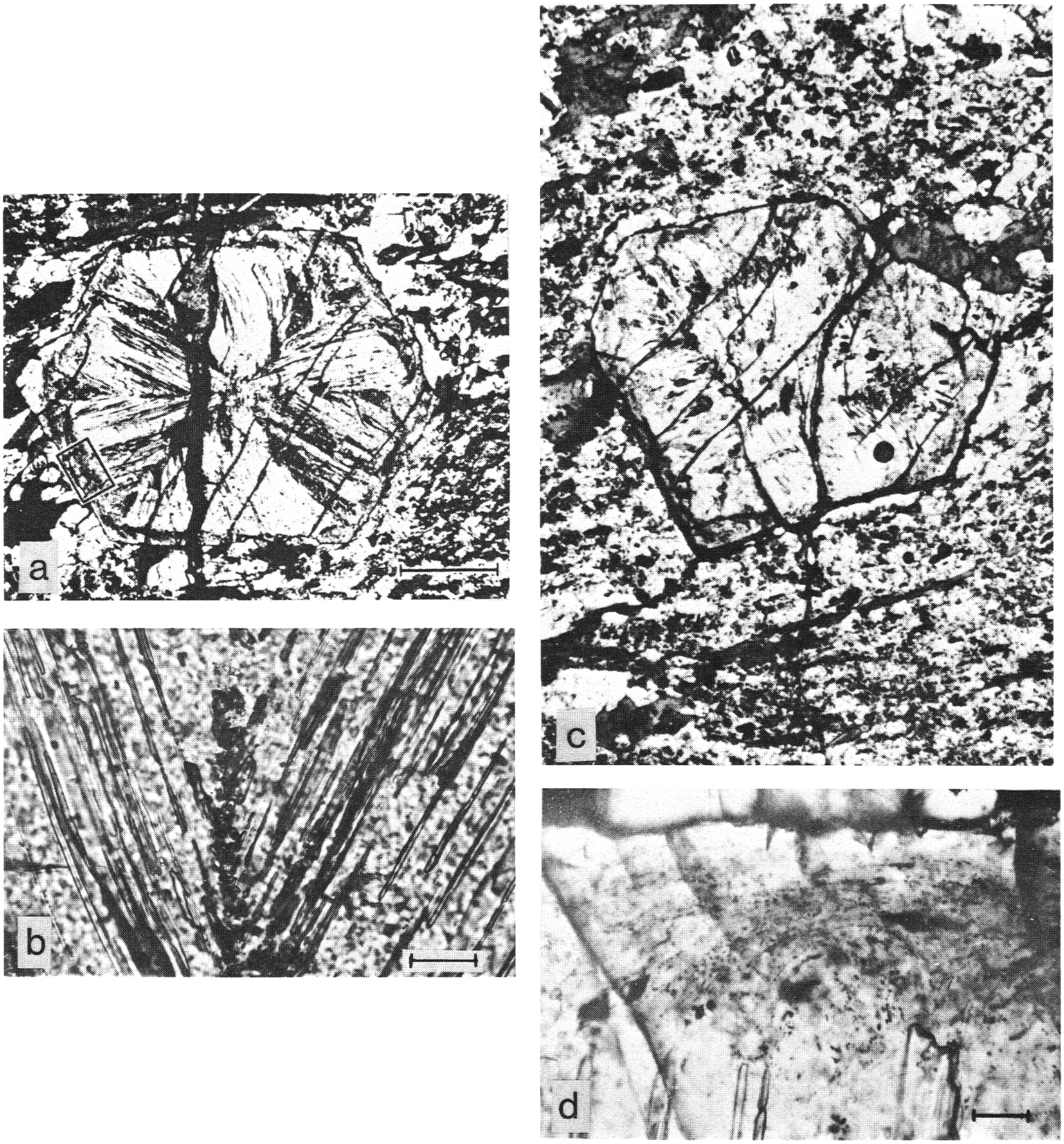

FIG. 2(*a*). Photomicrograph showing garnet porphyroblast sectioned through the centre. Zone 1, the graphite zone, and zone 2 (rim) are developed, with the inclusions of type 1 and 2 in the inner zone 1. Frame indicates enlarged area shown in fig. 2*d*. Scale bar approximately 330 μm. (*b*) Detail of inclusion patterns 1 and 2. The vertical train of equidimensional type 1 inclusions and the slender quartz tubes of type 2 are shown. Scale bar approximately 15 μm. (*c*) Oblique section of garnet porphyroblast showing variation in shape and angle between inclusions of type 1 and 2 as a result of the cut-effect. (*d*) Detail of fig. 2*a* showing the transition from zone 1 through the graphite zone to zone 2. The graphite zone characterized by abundant opaque inclusions fills depressions in the zone 1 surface above the inclusions of type 2. The type 2 inclusions define lineage boundaries between growth segments in zone. Scale bar approximately 20 μm.

the matrix, but have formed simultaneously with garnet growth. From different sections through garnets the shape and orientation of the inclusions can be accurately determined. They are arranged so that the long axes of the tubes are at 90° to the crystal faces, and make an angle of 30° with the planes containing inclusions of type 1. In sections cut parallel to crystal faces they appear circular and become progressively more elongate as the angle between the crystal face and the section increases (fig. 2*c*). Each of the tubular inclusions usually has uniform extinction, showing that the crystal lattice is continuous. Rarely inclusions may consist of two crystals with different crystallographic orientations. Variations in extinction direction from one inclusion to another indicate a random orientation of the quartz lattice relative to the garnet lattice. The absence of preferred lattice orientation of the quartz inclusions relative to garnet indicates that the interphase boundaries between quartz and garnet are non-coherent. The lattice continuity of quartz, however, shows that new material was added to the end of the tubular inclusion as the crystal face of the garnet propagated.

The consistent shape orientation of the tubular inclusions perpendicular to the {110} crystal faces shows that they have a similar orientation within the crystal lattice of the garnet in each of the pyramidal segments bounded by the planes rich in the type 1 inclusions.

Chemical zoning. The Magerøy garnets were analysed with an ARL electron microprobe at the University of Bergen. They show a symmetrical chemical zoning related to their internal optical zones (fig. 3). *Zone 1* which contains inclusions of type 1 and 2 is characterized by a high Mn content which decreases outwards and is mirrored by increasing Fe concentration (fig. 3). Ca shows a less pronounced, but distinct decrease from the core of the zone 1 to the graphite zone, and this is compensated by an increase in Mg. The *graphite zone* is marked by an antipathetic variation of Ca and Fe, Ca showing either a slight increase or a constant concentration. The concentration gradients for Mn and Mg remain almost continuous with those of zone 1. The inclusion-free *zone 2* forming the idioblastic rim shows an increase in Fe and Mn, and reduced concentrations of Mg and Ca.

A growth model and the origin of the inclusion pattern. The Fe and Mn concentrations in zone 1 in the Magerøy garnets are consistent with the fractionation model (Hollister, 1966). Garnet crystallization probably involved a reaction of the type:

$$\text{Chlorite} + \text{muscovite} + \text{quartz} \rightarrow \text{garnet} + \text{biotite} + H_2O \qquad (1)$$

As discussed above the timing of deformation and metamorphism indicate that the increase in metamorphic grade in the locality where the garnets preserve the type 1 and 2 inclusions was more rapid than in other areas with kyanite and staurolite-bearing metapelites in Magerøy. It is difficult to explain this very local variation in terms of variation of the regional geothermal gradient. Although the thermal effects of the igneous complex have not

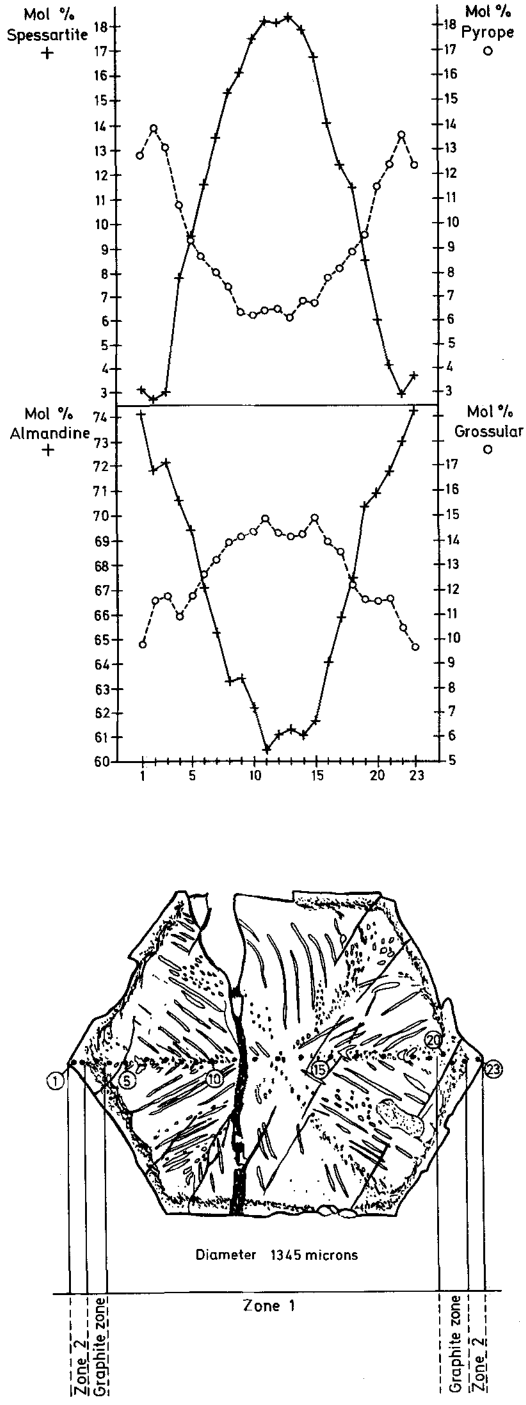

FIG. 3. Typical compositional profile of garnet from the studied locality (fig. 1). The analysis points (1–23) and the optical zones are indicated.

been studied in detail it is conceivable that the more rapid increase in metamorphic grade was caused by access to heat from the post-D_1 mafic/ultramafic intrusions. It is thus possible that the thermal gradient around this complex shortly after D_1 became more important in the studied area than the regional geothermal gradient.

The increase in temperature which initiated a continuous garnet-forming reaction of type 1, and the physico-chemical conditions resulting from this, controlled the growth defects in the crystallizing garnet porphyroblasts which is indicated by the inclusion pattern. A rapid increase in temperature would favour the growth of twins in the new mineral phases since twinned nuclei grow more rapidly than untwinned with increased supersaturation (Spry, 1969). The inclusion geometry alone cannot, however, be used as an indication of twinning, and as the garnet porphyroblasts invariably are isotropic it is unknown if they are twinned.

For the type 1 inclusion geometry it has been argued that these are relics of the matrix which were preferentially included along directions of rapid growth. This is in agreement with the conclusions drawn by Harker (1939).

The formation of the type 2 inclusions is considered to be the result of a growth mechanism where the garnet developed a cellular substructure (Chalmers, 1964). In this model the crystal faces advanced as a number of growth pillars. The development of such growth pillars may originate from a sheet growth mechanism where the growth occurred on nuclei formed by screw dislocations on the crystal faces (Verma and Krishna, 1966). Such dislocations and growth spirals on the crystal faces have been observed in synthetic garnets (Lefever and Chase, 1962). Following Smith's (1963, pp. 57–69) argument and terminology, growth from a number of screw dislocations on each face is likely at values of supersaturation below those causing dendritic growth. According to this mechanism the crystal face may advance as pillars, forming a crystal which is a cellular layerite. The present author will not attempt to relate directly the concepts of supersaturation and Chalmer's (1964) summary of the physico-chemical conditions necessary for the development of a cellular substructure in metallurgical experiments to those of solid state metamorphic conditions. If, however, the inclusion pattern of type 2 observed in garnets from Magerøy is analogous to that of the cellular substructure it implies an element of 'constitutional superheating' (analogous to constitutional supercooling in crystallization from a liquid) whereby the *T*-conditions for the stability of the reacting minerals in reaction (1) are exceeded.

The junction between the cellular segments or growth pillars form surfaces with plane defects in the crystal. Such surfaces are known as lineage boundaries, and are sites of less order and completeness in the crystal. Lineage boundaries of this kind form depressions on the crystal faces. In the present case the tubular quartz inclusions probably originated in such positions and continued to form depressions on the crystal faces as long as the growth took place on growth spirals (fig 2*d*). The variations in orientation of the quartz lattice which formed along the lineage boundaries may have been controlled by seeds of matrix quartz, or by random nucleation. Diffusion along lineage boundaries would be more equivalent to diffusion along grain boundaries than internal diffusion in the garnet crystals. The lineage boundaries would thus form loci where matter foreign to the growing garnet would be concentrated. The tubular quartz inclusions therefore probably represent reconstituted matrix quartz not consumed in the garnet-forming reaction (1) which have utilized the lineage boundaries to diffuse into as the garnet crystal faces advanced.

The graphite zone marks a change in both the chemistry and texture of the garnets. Fe shows a fall in concentration or a less pronounced gradient outward across the graphite zone, and this is compensated by antipathetic variation in Ca. It is possible that the garnet-forming reaction at this stage also involved plagioclase in a reaction of the type:

$$\text{Chlorite} + \text{muscovite} + \text{quartz} + \text{plagioclase}_1 \rightarrow \text{garnet} + \text{biotite} + \text{plagioclase}_2 + H_2O \quad (2)$$

Petrographic evidence for this is, however, lacking as plagioclase has not been identified as an inclusion. Reaction (2) is more likely than reactions involving epidote because this mineral is not present in the lower grade metapelites. The continued zoning of Mn and Mg is, however, consistent with the assumption that the continuous reaction (1) later involved plagioclase (Sivaprakash, 1981).

There is little evidence for a particular growth mechanism at this stage. The strong increase in the number of graphite inclusions may possibly be attributed to higher temperatures favouring the inclusion of finely divided material (Olimpio and Anderson, 1978). The prograde nature of reaction (2) is supported by the nucleation and growth of twinned staurolite and eventually kyanite. Models involving resorption of garnet by staurolite which have been advanced (Sivaprakash, 1981) as an explanation for the Ca and Fe gradients across the graphite zone fail to explain the concentration of inclusions in the present case.

Zone 2 is present in most of the garnet porphyroblasts as an inclusion-free idioblastic rim. It is, however, not completely developed on all porphyroblasts (fig. 2*a*). The chemistry of zone 2 is characterized by an outward increase in Mn and depletion of Mg. Fe increases towards the margins as in zone 1, while Ca decreases. The idioblastic and incomplete nature of this zone argues against the retrograde resorption model (Grant and Weiblen, 1971). There is no petrographic evidence that the Mn enrichment in zone 2 is a result of prograde resorption of garnet caused by crystallization of a more Mg-rich phase such as cordierite (Hollister, 1977). Retrograde replacement by chlorite is also absent. Marginal Mn enrichment is common also in other areas in Magerøy (Andersen, 1979). It is difficult to envisage a matrix reaction to produce the chemical zoning of zone 2. Hence it is proposed that the change in Mg and Mn concentration gradients is a result of retrograde cation exchange reactions (Yardley, 1977) during either a late stage of the D_1-D_2 interkinematic interval or D_2.

Conclusions. Zone 1 in the Magerøy garnets developed during a period of rapid temperature increase which was probably associated with the intrusion of a syn-orogenic mafic/ultramafic complex. Garnet crystals with growth imperfections developed at this stage. A relatively high level of supersaturation, but below that required for the development of dendrites, resulted in a growth mechanism producing cellular layerites. The cellular segments, formed by screw dislocations, are bounded by lineage boundaries. The tubular quartz inclusions of the type 2 inclusion pattern developed along the lineage boundaries, while the type 1 pattern formed by inclusion of the matrix along directions of rapid growth. The concentration of small inclusions in the graphite zone is tentatively ascribed to a change in the growth mechanism induced at higher temperatures.

The chemistry of zone 1 is thought to result from the continuous reaction (1) and is in accordance with the fractionation model. At higher temperatures plagioclase was involved in the reaction and this produced the chemical discontinuity across the graphite zone. The prograde nature of this zone is in accordance with the inclusion pattern. The reversal in the chemical zonation of Mn and Mg in zone 2 probably represents retrogression during subsequent regional metamorphism.

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