OROGENESIS MAGMAS AND METAMORPHISM*

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ABSTRACT

Tectonism, volcanism, plutonism and metamorphism are interdependent and contribute to the fabric of orogens and igneous rocks therein. Major lines of thought on problems relating to orogenesis in relation to igneous and metamorphic activity, generation of magma, rise of magma, and polymorphism and isostasy in crustal deformation, are outlined. The mechanics of emplacement of magma, at higher crustal levels, and the resultant fabric patterns are discussed at some length, as they are pertinent in interpretation of field data. The emplacement of granites and the major ideas in the generation of granite magma are discussed, and the new concepts of Buddington on the nature of emplacement of granite bodies, found at various crustal levels, presented. The tectonic implication of peridotites and serpentines, and the controversy over their mechanism of emplacement, are reviewed briefly. The concept of Hess that serpentinization below the Mohorovicic results in volume changes actuating mechanical movements such as uplifts, is suggested as applicable to the mechanics of uplift of sections of the stable Peninsular block of India.

Neither Volcanism nor Plutonism can be understood until we understand the formation of Maintain Chains.

—R. A. DALY, 1925.

INTRODUCTION

THE close relationship of igneous action to crustal deformation is exemplified by the prevalence of active volcanos along the major seismic belts of the earth's crust. Orogens are characterised by intense magmatic activity, as evidenced by chains of granite and granodiorite BATHOLITHS, and belts of ULTRAMAFITES. Similarly, the basement rocks in tectonic belts carry the impress of several cycles of metamorphism of varied character. The problem of deciphering the precise relationship between TECTONISM, VOLCANISM, PLUTONISM and METAMORPHISM is not simple, and requires careful analysis

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of a wealth of structural, stratigraphic, geochronological, petrographic and geochemical data. An attempt will be made here to outline some major lines of thought, and present some data of significance to field geologists.

GENERATION OF MAGMA

Crustal movements condition the generation of magmas and their passage to higher levels. Potential magma layers of the crust, when downfolded and pushed to deeper levels where the temperature is above their melting point, melt and generate liquid magma. Similarly, arching movements of the type proposed by Yoder result in crustal layers moving up to higher levels, and suffering sudden relief of pressure, resulting in their partial melting and generation of magma. The generation of parent magmas by tectonism conditioning the melting of appropriate crustal layers of the earth, has been envisaged by Stille, Buddington, Wahl and others.

MAGMA CYCLES

The cycle of magmatic activity in OROGENS differs in accordance with their antiquity. Younger orogens are characterised by (*i*) A geosynclinal phase with intrusion of BASIC and ULTRAMAFIC types (Ophiolites), and extrusion of SPILITIC lavas; (*ii*) A syntectonic phase with emplacement of GRANITE magma and intense migmatization, followed by late tectonic emplacement of GRANITIC and GRANODIORITIC batholiths; (*iii*) A post-tectonic volcanic eruptive phase with extrusion of ANDESITIC lavas and (*iv*) An eruptive phase with extrusion and injection of BASALTIC magma after which the region ceases to be a mobile belt. In older orogens of the Archæan, a different pattern is envisaged, as exemplified in the Fennoscandian shield, where a zone of PRIMOROGENITIC granites with extensive granitization and BASIC and ULTRAMAFIC volcanic action, is followed by a zone of serorogenic granites, actuating migmatization and granitization, with a final phase marked by emplacement of post-orogenic granites.

PARENTAL MAGMAS

During orogenesis, the generation of four primary parental magmas envisaged by Wahl (1949), (1) SPILITIC magma grading to a PICRITIC types, (2) GRANODIORITIC magma which will differentiate to a variety of rock, varying from GRANITES to PERIDOTITES, (3) BASALTIC magma and (4) POTASH GRANITE magma (granite eutectic composition). When crustal movements attain a cratogenic character THOLEIITIC and OLIVINE-BASALTIC magmas are generated the former from the upper Simatic layer and the latter from greater depths, while granitic magma differentiates into POTASH GRANITE and GABBRO-ANORTHOSITE-NORITE, CHARNOCKITIC magmas differentiating into granitic, syenitic and granodioritic variants as suggested by the writer (Subramaniam, 1959) and FOYAITIC magmas differentiating into a variety of alkalic sub-magmas, may also be cratogenic in character. PERIDOTITIC and PYROXENITIC magmas may also be generated by fusion of the lowest part of the simatic shell under cratogenic conditions.

Buddington (1943) has visualised a primordial layering of the basaltic layer of the upper crust, simulating it to that obtaining in density stratified sheets like the Bushveld, Stillwater and Skaergaard. According to his diagrammatic representation, deformation of the crustal layers will have essentially the effect of displacing the fusion curves for each rock layer with respect to the Temperature-Depth curve. When the temperature-depth curve is raised relative to and lies above the fusion curve for the respective kind of rock, the appropriate magma will be formed. While gabbroic magma would be dominant and recurrent as it can form throughout a wide environmental range, peridotite magma will be generated only under exceptional structural dynamics. Buddington has envisaged the generation of a gabbroic anorthosite magma by partial melting of the Bytownite-Anorthosite layer. The position of this crustal layer as envisaged is such that its melting can take place only under exceptional conditions. The exclusive occurrence of large masses of intrusive anorthosite, in the Pre-Cambrian, and the rarity of an extrusive equivalent of this type of anorthosite, are in conformity with the hypothesis.

POLYMORPHISM AND ISOSTASY

In 1937, Bernal and Jeffrys suggested that polymorphic rearrangement of the crystal structure of OLIVINE $(MgFe)_2 SiO_4$ might explain certain discontinuities within the mantle. Mason (1953) proposed that an increase in the amount of a denser polymorph could lead to the contraction of the earth resulting in crustal shortening and orogeny. It is suggested that polymorphic transitions take place along a fairly wide zone, as the rates of transformation vary with depth, temperature and pressure. The volume changes resulting from polymorphic transitions will produce a purely mechanical effect, the increased pressure due to such volume changes resulting in fracturing of the crust. Relative motion of molecules during polymorphic transitions may also dissipate shear stresses. Polymorphic transitions with consequent volume changes may be a significant factor in Isostatic adjustments, which in turn induce geochemical changes actuating melting of crustal layers. Similarly, geochemical phase transformations at sub-crustal levels result in large volume changes, which may induce epeirogenic movements and uplifts. Hess (1955) has speculated on volume changes consequent on serpentinization of olivine rock below the Mohorovicic, to account for epeirogenic movements of the sea floor, and the uplift of the Colorado plateau. It is not inconceivable that a similar mechanism may have been operative in the uplift of certain sections of the stable peninsular block of India.

MECHANICS OF EMPLACEMENT OF IGNEOUS ROCKS

Emplacements of magma at higher crustal levels involves a variety of processes dependent on the nature of the magmatic source, time of emplacement, and crustal tectonics. These are classified as below (following Professor Buddington's lectures)*:

Mechanism	*Mechanics*	*Fabrics*
1. *Quiescent Emplacement:*		
(*a*) *Stoping—*		
(i) Piecemeal stoping	(i) Magma is generally less dense than country rock and therefore tends to rise along joints, fractures, etc.	(i) Batholiths (?)
(ii) Ring fracture stoping.	(ii) Blocks of country rock work free and sink into magma chamber. In a few instances country rock is lighter than magma—*e.g.*, blocks stoped from the base of diabase sheets and rise upward.	(ii) Blocks of country rock surrounded by fractures sink into magma chamber; sometimes they are moved up.
(iii) Major stoping	(iii) Large blocks of basement rock pushed up by rising magma and absorbed in the magma chamber.	(iii) Batholiths (?) with large blocks of crustal material broken apart by orogeny.
(*b*) *Entry of magma into pre-existing spaces—*		
(i) Tensional fractures	(i) Tensional fractures in plateau volcanic regions lavas are erupted from fissure which are probably of tensional origin.	(i) Fissure lava eruptions and island are volcanics.
(ii) Pore space	(ii) The origin of the fissures is not completely understood but it would seem that they penetrate to the depth of the "basalt layer" and thus permit the rise of basaltic magma.	(ii) Magma or magmatic vapours permeate pore space.

* Graduate Course Lectures on Structural Petrology given at the Princeton University.

Mechanism	*Mechanics*	*Fabrics*
(iii) Subcrustal space	(iii) Rise in response to differential pressure.	(iii) Doubtful.
(c) *Subsidence with consequent rise of magma—*		
(i) Cauldron subsidence	(i) Involves development of ring-type fractures and settling of crustal blocks into magma chamber. May be subaerial or sub-terranean.	(i) Cauldrons, ring dykes and cone sheets.
(ii) Floor subsidence	(ii) Involves sinking of the floor of intrusive masses into large magma chamber below.	(ii) Lopoliths and ethmoliths
II. *Forceful Injection:*		
(a) *By moving overlying rock—*		
(1) Upthrusting (2) Doming (3) Lifting	(1–3) Pressure of magma forces rock upward. Therefore characteristic of shallow depth—hypabyssal range.	(i–iii) Sills with flat dips ; flat lying sheets; Laccoliths, Bysmaliths. Cone sheets with vertical displacement, stocks, Batholiths (of shallow depth), and Feeders to layered bodies.
(b) *By thrusting country rock aside*	Wall rock thrust laterally by force of magma. Believed characteristic of intrusion at depth and found in association with larger intrusive masses.	Batholiths with marginal thrusts and peripheral foliation.
(c) *By combinations of* a *and* b.	..	Laccoliths and some ring dykes and cone sheets.
(d) *By thrusting country rock downward*	Emplacement by downward thrusting of roof.	Ethmoliths.
(e) *Displacement direction doubtful*	Passive emplacement in space created by crustal movements induced.	Where displacement direction is not definitely known the form may be a Phacolith or Harpolith.
III. *Diapiric:*	Analogous to the emplacement of salt domes—strata are thrust outward and upward to allow emplacement. This is perhaps most characteristic of orogens.	Large tear-shaped intrusives which may have roots.

Mechanism	*Mechanics*	*Fabrics*
IV. *Chemical emplacement:*		Batholithic massifs
(*a*) *Regional melting at depth*		
(1) Magma generated and crystallizes in same place	Involves heating of sialic material and consequent generation of magma. This may be accomplished by down-buckling of the crust so that it is brought into a zone of high temperature. Possibly the granitic rocks of orogenic regions are developed in the sialic material which is depressed in a tectogene.	
(2) Magma generated and moves to higher level prior to crystallization	The palingenetic magma may either crystallize *in situ* or may be intruded into overlying rocks. If it is intruded, then the mechanics involved may be diapiric.	
(*b*) *Local melting in the upper crust by heat of invading magma*	This concept involves superheat in the invading magma. Not important as far as emplacement is concerned.	
(*c*) *Melting through the action of volcanic gas*	Of little importance in large-scale emplacement.	
(*d*) *Replacement through the action of granitizing liquids or gases*	Involves the concept of transforming solid rocks to rocks of granitic character, without passing through a magmatic stage. Several mechanisms postulated, but none have been substantiated.	

In summary it may be said that one or more of the following processes may have been important in the emplacement of a given igneous mass:

(i) Quiescent upward motion of magma.

(ii) Forceful injection of magma.

(iii) Diapiric injection of magma.

(iv) Replacement,

The forces impelling the magma for each of the first three processes must necessarily have varied. Presumably, the difference in specific gravity between magma and country rock is sufficient to permit quiescent emplacement by stoping, cauldron subsidence, etc. Forceful injection, however, requires additional impelling force. The nature of this additional force is not known but most investigators believe it to be consequent upon orogeny, magma being forced upward by lateral stresses. Diapiric injection probably involves a combination of both.

Several fabric patterns serve to distinguish the mechanics involved in the emplacement of igneous rocks. The most diagnostic are those characteristic of forceful injection. These are listed below:

(*a*) External fabrics indicative of magmatic pressure:

- (i) Outflow of magma at a high elevation.
- (ii) Upward motion of inclusions.
- (iii) Uplift of roof rocks—folding, jointing, faulting.
- (iv) Updrag of bedding, fold axes, linear structures, etc.
- (v) Peripheral folds.
- (vi) Peripheral foliation planes.
- (vii) Faults.
- (viii) Border mylonites.

(*b*) Internal fabrics indicative of forceful injection:

- (i) Linear and planar flow structures.
- (ii) Orientation of inclusions, segregations, etc.
- (iii) Primary fracture systems—cross joints, longitudinal joints, diagonal joints, primary flats joints.
- (iv) Flexures in flow layers.
- (v) Marginal thrusts.

Fabrics of the above type are not observed in masses emplaced by stoping; some, however, may be present in intrusives emplaced through diapiric mechanics.

Rise of Magma

Movement of magma is dependent on several factors and the mechanics of intrusion of thin fluid magma differs from the mechanics of intrusion of viscous magmas.

Causes of magma motion:

(1) Gravitative adjustment—Modification of density by vesiculation, partial crystallization or changes of temperature (Passive).

(2) Lateral thrusts—Crustal movements and magma movements are co-ordinate but neither can be demonstrated being cause of the other (Aggressive).

Extrusion is also controlled by crustal tectonics. Fissure eruptions are characteristic of region which have suffered vertical crustal movements where lateral movements are only consequential, while central type of eruption is characteristic of areas which have suffered lateral movements of the Alpine type.

EMPLACEMENT OF GRANITE

According to Wahl (1949) isostatic adjustment during orogenic down-buckling results in the partial fusion of feldspathic components of the rocks. The molten feldspars will naturally carry quartz, water vapour, and small amounts of mafic material in solution and thus approximate in composition, an ideal granite. The generation of granitic liquid has been discussed at great length by Wahl (1936, 1943), Sederholm (1933), Bowen (1928), Eskola (1932, 1933, 1936, 1955) Holmes (1932), Stille (1939), Buddington (1943), Paige (1955), Reed (1955), Gorai (1960) and others. The major processes envisaged are:

(1) By fusion of geosynclinal sediments (Palingenesis).

(2) By refusion of the base of the granitic layer of the earth (Protectite).

(3) By differentiation of a syntectic magma formed by the solution of granites or other salic material in basaltic magma (migma + magma).

(4) Differentiation of basaltic magma as such (True magma).

(5) Through partial refusion of the upper mantle under relatively high pressure condition.

In recent times, the older French and Fennoscandian schools of thought on the origin of large granite massifs by a process of granitization has been ably advocated by Reed (1955, 1957) in a series of addresses. He has proposed a GRANITE SERIES, correlating time and crustal level, with formation of granitic rocks in an orogenic belt. Recently, Buddington (1959) has critically reviewed the existing tectonic data, particularly on North American Granites, and offered a major revision to Reed's concepts. Buddington has evaluated the emplacement mechanism on the basis of the external and internal structures of granite bodies found at different crustal levels, or rather at physical conditions obtaining at such crustal levels. He has suggested the terms CATAZONAL, MESOZONAL and EPIZONAL to granites formed at temperature depth-zones obtaining at depths of 7–12 miles, 5–9 miles and

0–4 miles. Buddington has pointed out that granites of the epizone are wholly discordant, those of the mesozone partly concordant and partly discordant, and those of the catazone predominantly concordant. Granitization is regarded by him as the major process involved in the formation of catazonal granite massifs, subordinate in the formation of granites of the mesozone and minor or local in the formation of epizonal plutons.

ULTRAMAFIC MAGMAS AND TECTONISM

The tectonic implications of large masses of PERIDOTITES and SERPENTINES have been discussed by Benson (1926) and Hess (1938, 1939, 1954, 1955). The latter has expounded at length the mechanism of emplacement of such ultramafic bodies, the nature of the primary magma and its source, the types of ultramafic rocks in various tectonic settings, and the relation of large-scale serpentine belts to global deformational features like the ISLAND ARCS. During a study of the gravity anomalies in the West Indian islands arc, Hess noticed the close association of a belt of serpentinized peridotite intrusions with a zone of strong negative anomaly. The anomaly is interpreted to be an intense zone of deformation, representing a major downbuckle, or TECTOGENE. During its formation, the base of the relatively strong upper crust came into contact with a peridotitic substratum whose upper portions underwent partial fusion and were squeezed off. The relatively rigid and strongly deformed downbuckle allowed the hydrous peridotite magma to migrate upwards and get emplaced either along the axis of the downbuckle or on either side of it.

The nature of the ultramafics during emplacement has been a matter of controversy, the field evidence being opposed to the conclusions based on experimental studies on the system MgO–SiO_2–H_2O. The field geologists conceive of a PERIDOTITE MAGMA rich in water emplaced in a fluid state, while the experimentalists preclude the possibility of a peridotite magma at such temperatures. Emplacement of PERIDOTITE or SERPENTINE in the solid state with their mobility facilitating movement along tectonic zones, has been established in certain cases, but this mechanism is not applicable in many other instances. Other lines of field and laboratory evidence strongly favour emplacement of a liquid ultramafic magma.

MacKenzie (1960, pp. 312–13) has discussed the temperature of intrusion of the Tinaquillo peridotite from Venezuela, and based on the structure and composition of garnets and pyroxenes at the contacts, estimated the temperature of intrusion to be between 800° C. and 1,000° C. This problem merits further investigation in the field and laboratory. Reed (1954) regards serpentines anomalous and has aptly described them as slippery tectonic pods.

Yoder and Tilley (1958–59, pp. 89–94) have experimentally sought elucidation of Fermor's conception of an Infra-plutonic shell of eclogite in the sub-crustal zone. They have regarded that eclogites would be a potential source of basalt. By varied experimentation under appropriate conditions, they have demonstrated that eclogites could be converted to basalt, pyroxenite or hornblendite, and by partial melting of eclogite either of two major types of basalt may be generated.

TECTONISM AND METAMORPHISM

Changed physical conditions induced by crustal deformation such as downfolding to deeper levels and arching or doming to higher levels, will result in mineralogical and textural changes in the rocks of the crust. The metamorphic changes attendant on deformation have been defined in the depth-temperature zonal classification of Becke, Grubennmann and Niggli, and the Facies concept of Eskola. Recent experimental work has revealed that factors other than temperature may lead to the formation of rocks generally thought to have formed in a particular depth-temperature intensity zone. For example, eclogites which are generally regarded as Catazonal and formed under highest pressure conditions, are also found in younger orogens in association with low pressure assemblages. The role of water and other fluids, moving along the intergranular boundaries and acting as a catalyst has been emphasized; the movement of these pore fluids is perhaps controlled by crustal movements. The basement of an orogen does not remain passive during diastrophism, but is rejuvenated, by differential anatexis and introduction of granitizing fluids and ichors, consequently attaining mobility to the extent of initiating intrusion. The mobilised infra structure forces itself up into the super-structure as visualised by Wegmann (1935). High grade metamorphism, granitization and orogeny may therefore be regarded as related events. According to Reed (1954) widespread low grade metamorphism is associated directly with orogeny, followed later by superimposition of granitization metamorphism. He regards permeation of metasomatic solutions to be related to regional metamorphism.

According to Waters (1955) in a crustal downbuckle, of the tectogene type, water and other easily removable constituents move out of the geosynclinal prism and mix up with tholeiite, modifying it to an explosive andesite. Continued metamorphism of the tectogene root results in the emplacement of TRONDJHEMITIC and GRANODIORITIC batholiths. Prolonged anatexis will leave behind a roof of GREENSTONES, LIMESTONES and SERPENTINES which are transformed by dehydration, actuated by increasing metamorphism, to AMPHIBOLITES, SKARNS, and URALITIZED or BIOTITIZED ULTRAMAFITES. Partial local melting of the rocks will result in the formation of alkalic mafic lavas which are erupted.

SOME PROBLEMS

Except for an excellent summary by Krishnan (1953) little or no attempt has been made in India to decipher the relationship between Tectonism, Igneous activity and Metamorphism. A wide field is open to workers, and the older publications of the Geological Survey contain a wealth of valuable data meriting reinterpretation and analysis.

The Archæan shield area of the Indian Peninsula offers unrivalled scope for studies of precambian tectonics. The Charnockite suite of rocks, and the Alkalic rocks of MADRAS, KERALA, ANDHRA, ORISSA and RAJASTHAN, which are perhaps cratogenic, merit detailed studies, particularly with regard to their tectonic setting. Similarly the Archæan Ultramafics which have undergone metamorphic reconstitution have to be carefully examined and their primary nature established. The granites of India present a variety of complex problems concerning their tectonics, emplacement mechanism, and geochemistry, while the Deccan basalts offer a rare challenge. The mechanism of extrusion of the Deccan basalts is not clear and the presence of flows which can be traced uninterrupted to distances of over 50 miles is a remarkable feature.

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