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A Tectonically-Controlled Rock Cycle

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A TECTONICALLY-CONTROLLED ROCK CYCLE

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ABSTRACT

A rock cycle is proposed, in which geological processes of erosion, deposition and metamorphism are primarily controlled by vertical movements of crustal blocks. This rock cycle is considered to provide a framework for the scientific study of catastrophic episodes of Earth history.

INTRODUCTION

Geological texts on sedimentary petrology generally reveal a strong preference for adopting 'modern analogues'. Most will give detailed descriptions of a wide range of modern sedimentary environments. Fluvial deposits include those laid down by meandering and braided rivers and by alluvial fans. Sedimentation in other terrestrial environments involve erosion and deposition in deserts and in glacial areas. On the continental margins are found more varied sites of deposition: deltas, coasts, shorelines, siliclastic shelf seas and carbonate shelf seas. Deep sea environments have abyssal plain sedimentation and the input of clastics via submarine fans. These categories are familiar to all sedimentologists, the majority of whom would say they are directly applicable to most ancient environments. The underlying philosophy here is that 'the present is the key to the past'. The approach of most textbooks and working sedimentologists is governed by a deeply held commitment to a philosophy known as Lyellian Uniformitarianism.

It should be noted that the textbooks mirror the teaching practice in almost all university courses on sedimentary geology. One must ask whether it is right for students to be steered so early in their studies towards a wholesale adoption of modern analogues for the interpretation of ancient rocks? The contemporary trend in geology is away from Lyellian Uniformitarianism, and there is a growing recognition that the present-day norms are not the key to the past. Thus, Ager (1) writes:

> In other words, we have allowed ourselves to be brainwashed into avoiding any interpretation of the past that involves extreme and what may be termed 'catastrophic' processes. However, it seems to me that the stratigraphical record is full of examples of processes that are far from 'normal' in the usual sense of the word. In particular we must conclude that SEDIMENTATION IN THE PAST HAS OFTEN BEEN VERY RAPID INDEED AND VERY SPASMODIC. This may be called the Phenomenon of the Catastrophic Nature of much of the Stratigraphical Record (pp.46-47).
>
> In other words, the history of any one part of the earth, like the life of a soldier, consists of long periods of boredom and short periods of terror (pp.106--107).

The problem that must be addressed by all sedimentary geologists is that of organising ideas into a coherent whole. A framework for study is required - and this is all too conveniently provided by contemporary patterns of erosion and deposition. The picture is encapsulated in the conventional 'rock cycle' which was first developed by James Hutton, sometimes referred to as the 'Father of Geology'. The influence of his particular contribution to the study of historical geology is difficult to overestimate. It appears to have dominated the thinking of all the Nineteenth Century geologists, including catastrophists like Cuvier, Buckland and Miller, and it is the unquestioned orthodoxy of Twentieth Century geology. Yet Hutton's thinking was rooted in a marriage of Empiricist philosophy and Deism and, contrary to popular opinion, was not a product of extensive field study (2,3,4).

Since the Huttonian rock cycle invokes present-day processes, it is foundational to Lyellian Uniformitarianism. It is suggested here that the continuing dominance of Lyellian geology is because no real challenge has ever been made to the Huttonian rock cycle. Geology students are introduced to this cycle at the outset of their studies, so that their mindset is established. Since few question the foundations of their chosen subject, this early exposure to uniformitarian concepts ensures that all subsequent views are coloured by it.

In recent years, the role of tectonic processes in the formation of sediments has been recognised and given more prominence. To take one example: few students of English geology will be unaware of the Alston and Askrigg blocks in the Pennines. Tectonic movements of these blocks are invoked to explain observed patterns of sedimentation. In some instances, evidences for synsedimentary faulting are present, showing even more clearly that tectonic activity and sedimentary processes are linked. Tectonic features and catastrophic events are now quite widely recognised, but are still fitted into the framework dictated by the Huttonian rock cycle (5).

This paper is an attempt to describe a rock cycle that is dominated by tectonically-controlled processes. This new model provides for the "short periods of terror" as described by Ager, but has little provision for the "long periods of boredom". These long ages of geological time are essential for evolutionary theories but are not necessarily required by the rock record. Figure 1 provides an overview of the proposed rock cycle. In the interests of brevity, the processes are outlined below without extensive elaboration.

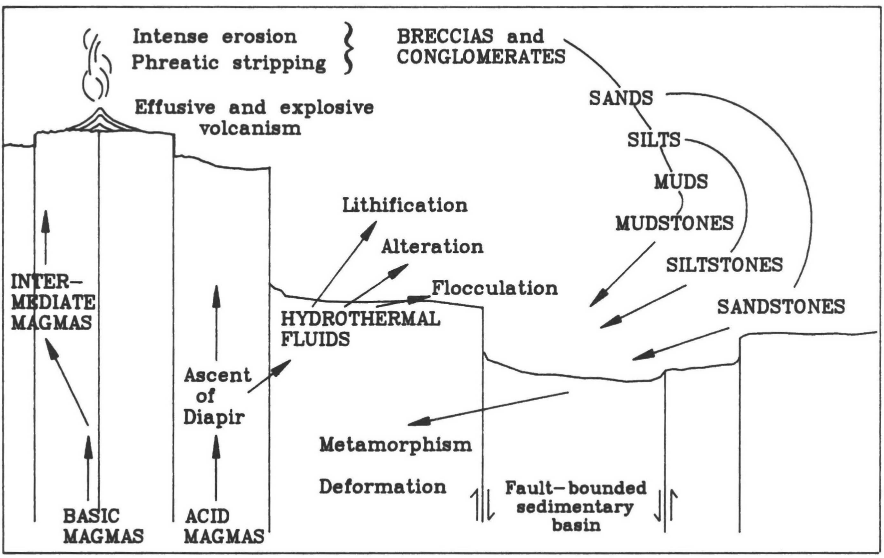

Figure 1. A tectonically-controlled rock cycle.

IGNEOUS PROCESSES

Basic and Intermediate Rocks

In this model, basic magmas originate by partial melting of upper mantle ultra-basic rocks. Since these magmas have low viscosity, they are able to move rapidly through faults and other conduits in the Earth's crust towards the surface. Fractional crystallisation of basic magma leads to the formation of magma of intermediate composition. If conditions are suitable, magmas emerge on the Earth's surface to form volcanoes, lava flows and lava sheets.

Acid Rocks

Acid rocks are considered here to have a source separate from that of basic and intermediate rocks. In this model, they derive from the partial melting of pre-existent continental crust. The magmas are highly viscous and are not able to move easily up conduits by convective flow. Consequently, these magmas form large diapirs at depth. Their vertical movements are described by Stokes Law:

$$V = \frac{2 r^2 g \Delta\rho}{9 \eta} \quad (1)$$

V = velocity of rise of diapir (ms^{-1})
r = radius of diapir (m)
g = acceleration due to gravity (ms^{-2})
$\Delta\rho$ = density difference between diapir and crustal rocks (kgm^{-3})
η = dynamic viscosity (Pas)

Using $g = 10ms^{-2}$, $\Delta\rho = 300kgm^{-3}$, $\eta = 10^{12}Pas$, and a diapir radius of 2 km, a molten granite mass will pass through the whole of the Earth's crust in less than half a year. Larger diapirs are even faster. The situation is certainly complicated by the loss of heat energy by contact with the country rock, although this cooling effect is likely to reduce the size of a diapir rather than its temperature. Consequently, it is possible for a magma body to reach the surface soon after it is formed. Since many granitic diapirs appear to have had considerable amounts of water dissolved in them, solidification before reaching the surface is anticipated. However, in a typical case, upward forces would still act on the body so that it would continue to rise, resulting in the elevation of a tectonic block and the generation of innumerable fissures. These fissures have an important role to play in the subsequent convective cooling of the pluton, as is explained in the following sub-section. If the pluton is near the surface when it solidifies, it may continue to rise tectonically and introduce much faulting, fracturing and folding in the overlying strata. Granitic diapirs that actually reach the surface produce large volumes of ash fall and ash flow tuffs and also rhyolite flows. Magmatic fluids expelled from solidifying magmas are responsible for the formation of pegmatites and hydrothermal vein deposits. The escaping fraction of these liquids may provide chemicals which influence contemporaneous sedimentation and diagenetic processes.

Convective Cooling of Large Magma Bodies

Most calculations of cooling rates for large magma bodies assume that conductive energy heat loss predominates. The country rocks are considered to be dry, with gentle temperature gradients, so that cooling timescales extend over hundreds of thousands or millions of years. However, recent observations at the mid-ocean ridges indicate that, under certain conditions, convective heat loss is of major importance.

Exploration of the ocean floor in the vicinity of the mid-oceanic ridges has revealed the presence of hydrothermal vents and dependent ecological systems (6). Hot rocks under the mid-ocean ridges are being cooled extremely efficiently by the large-scale movements of sea-water through the basaltic ocean crust. At an East Pacific Rise location, some black smoker vents had water temperatures of about 350 degrees centigrade and discharge velocities of 2-3 metres per second. Macdonald et al. (7) demonstrate that the convective energy loss from one small black smoker is approximately the same as that from conduction through a 60 kilometre square of the Earth's surface. The vents are short-lived because they are so efficient: convective heat flow slows when the source rocks are cooled. Further useful discussion is provided by Cann and Stiens (8).

It would appear realistic to infer large-scale convective cooling for all magma bodies in contact with groundwaters where the country rocks permit circulation. It is necessary to investigate whether convective cooling has played a significant part in the cooling of continental plutonic rocks. Parmentier and Schedl (9) have considered the thermal aureoles of the Mull intrusive complex,
the Skye Cuillin gabbro, and the El Salvador porphry copper deposits. The shapes of the metamorphic aureoles are inconsistent with purely conductive heat loss but can be explained by invoking convective activity. Recent reports from the Soviet Union deep drilling project (10) have revealed the presence of considerable volumes of water at depths previously thought impossible because of the high pressures exerted by overlying rocks. With water existing at depths of up to 12 kilometres, the opportunities for invoking convective cooling are greatly extended. In the tectonically-controlled rock cycle, the magma bodies themselves are considered to produce fractures in the country rock, thus permitting a freer circulation of waters at depth.

Crystal Growth in Magmatic Liquids

It is widely believed that coarse-grained granites and gabbros have had a very slow cooling history. This sub-section suggests that this belief is inferred and is not warranted by experimental and theoretical research programmes into the topic.

Most of the information on the petrology of igneous rocks is in the form of phase diagrams applicable to magmas in an equilibrium state. Before 1975, experiments on the rates of crystal growth were exceedingly few. An excellent summary of relevant work is provided by Dowty (11). Two factors are of major importance: rates of nucleation and rates of crystal growth.

Experimental work to determine nucleation rates is extremely difficult. Most of the relevant studies have reported nucleation densities to provide a basis for comparing minerals measured by the same investigator. Lofgren (12) has concluded that nucleation behaviour is more important than crystal growth rates in producing various mineral features and rock textures.

Crystal growth rates have been measured, mostly for single-component melts. Maximum growth rates for common minerals are of the order of 1×10^{-5} centimetres per second. Water in the melt tends to decrease growth rates; multiple-component melts tend to have smaller crystal growth rates than single-component melts. More realistic figures appear to be of the order of 1×10^{-7} centimetres per second, obtained in studies of wet granitic melts.

Whilst maximum cooling times may not be inferred from studies of this kind, it is possible to comment on minimum cooling times. The number of seconds in one year is 3.15×10^{7}, which should be compared with the crystal growth rates of wet granitic melts. Timescales of 1 - 10 years might be considered realistic minimum cooling times. A comment by Luth (13) provides a fitting conclusion:

It is frequently assumed that the presence of large crystals in these phases implies slow growth over long periods of time. Although this may be the case, the intent here is to demonstrate that it does not necessarily hold (p. 405).

EROSION AND DEPOSITION PROCESSES

Both volcanic and plutonic activity lead to intense weathering of surface rocks. Elevation of crustal blocks because of igneous activity at depth increases precipitation and erosion. Volcanic dust introduced to the atmosphere provides nuclei for condensation and seeds torrential rainfall and flash flooding. In a situation where vast quantities of heat energy are released, evaporation of water occurs readily and the hydrological cycle is intensified. Since the uplifted ground is full of joints, cracks and faults because of tectonic movements, it can be weathered swiftly and the debris transported to lower altitudes. Extensive deposits of alluvial fan breccias and conglomerates around mountainous regions testify of such abnormally erosive processes operating in the past. Examples include the fanglomerates around the Troodos Mountains of Cyprus and the Molasse deposits of the Alps.

Continuing transport of materials by rivers and oceanic waters leads to the winnowing and sorting of sediments into sands, silts and muds. Weathering of minerals is both physical and chemical, and both may be intense. Chemical weathering may be further promoted by the presence of fluids of volcanic origin. A considerable proportion of clay minerals may be derived from volcanic ash (14).

An additional catastrophic mechanism for erosion is provided by phreatic stripping. Hot igneous bodies emplaced at depth initiate the circulation of groundwaters. The water temperatures will generally exceed 100 degrees Centigrade because of the pressure exerted by the overburden. So, around a magma body, a shroud of superheated water develops. A sudden release in pressure may lead to remarkable effects. Initially, some super-heated water changes into steam which instantly seeks to occupy a much greater volume. The resultant high pressure physically lifts the overburden and forms fractures through which steam can escape. However, this is but the start of an avalanche process, as continuing vapourisation of superheated water leads to a violent explosion. The overburden, together with all the sediments containing the superheated water, is erupted into the atmosphere. In this way, large volumes of water-permeated materials may be stripped away from above a hot pluton.

Probably the best examples of the phreatic stripping mechanism are found in Yellowstone National Park in the USA. At least ten craters in the Park, ranging in diameter from a few tens of metres to about 170 metres, were identified as hydrothermal explosion craters by Muffler et al (15). Subsequently, Mary Bay in Yellowstone Lake, with a diameter in excess of 2.5 kilometres, was added to the list by Wold et al (16). Explosions have been associated with the waning stages of a glacial period and the following mechanism has been suggested. It is thought that an ice-dammed lake existed over a hydrothermal system. The waters permeating the unconsolidated sediments were superheated, but the situation was stable because of the confining pressure. When the dam broke because of the ablating ice-field, the lake was drained rapidly, reducing the pressure on the hydrothermal system. At a critical moment, some of the superheated water flashed to steam, violently disrupting the water-logged sediments, further reducing the pressure and initiating a run-away explosion. The debris ejected from Mary Bay may be inspected readily in sections created by road cuttings. Additional examples of hydrothermal explosion craters have been reported from California, Nevada, New Zealand and Italy (15).

In the Global Flood cataclysm, all the ingredients of hydrothermal explosions are present, but on a much grander scale. Wet sediments overlying hot magma bodies may be removed catastrophically when tectonic movements reduce the confining pressures exerted by floodwaters.

Tectonic processes not only influence patterns of erosion, but also patterns of deposition. Sedimentary basins are formed by the lowering of tectonic blocks. These basins may develop as graben-like structures, with fault movements linked to igneous activity. A further mechanism is provided by the collapse of the Fountains of the Great Deep during the Global Flood (17). Movements of sediment into these fault-bounded basins are not normally considered seriously by the advocates of Lyellian uniformitarianism. However, this model of catastrophic sedimentation provides a framework for interpreting such distinctive features as good lateral persistence of beds, abrupt transitions between beds, regular and thick bed thicknesses, constant orientation of bedding planes, and planar unconformities.

The features described above are well displayed in the classic Grand Canyon sections. The difficulty for the Huttonian rock cycle approach to interpretation is that present day processes fail to do justice to these evidences. Modern environments do not lead to these large-scale distinctive features. Ample scope exists for non-uniformitarian depositional models for Grand Canyon rocks. Catastrophic mechanisms will need to be adopted in order to transport sedimentary material on a different scale to that occurring in the present day. This is not to imply that it is of little value to study modern-day environments, but it does mean that they should no longer be regarded as the key to the past. Rather, interests should be developed in different modern analogues, as are found in catastrophic events, and in what they can achieve (18). It means looking at scaling factors, so that catastrophic processes can be brought within the orbit of scientific analysis.

The widespread occurrence of cyclicity in sedimentary rock units has provided many puzzles for traditional gradualistic models of sedimentation. To account for the field evidences, sedimentologists have found it necessary to propose quite complex, and often contrived, patterns of erosion, deposition and base-level changes. A vigorous challenge to this approach has been made by Goodwin and Anderson (19), who have cast aside overtly the old paradigm and have boldly proposed an alternative. Their hypothesis of punctuated aggradational cycles (PAC) focuses attention, not on a localised area of deposition, but on the sedimentary basin considered as a whole. Base-level changes affecting the basin affect all the sedimentary processes taking place within the basin. This model is one which has considerable explanatory power and deserves extensive discussion. Of the mechanisms considered by Goodwin and Anderson, one is particularly relevant to the tectonically-controlled rock cycle: episodic crustal movements. Catastrophic events in the history of the Earth provide a framework for further developing the PAC hypothesis.

Other features of the rock record which seem particularly suited to catastrophic interpretations include the mixing of sediments of different character (eg sandstones and limestones), syndepositional faulting, and turbidic sedimentation (20).

Within the tectonically-controlled rock cycle model, sedimentation occurs relatively fast. Even muds may be rapidly deposited, as flocculation rates increase with the density of clay particles and also with the presence of salt.

Disturbed ecosystems must ensue from these catastrophic processes. The depositional environments envisaged provide ideal sites for the preservation of body fossils, trace fossils and sedimentary structures. Rupke's (21) discussion of ephemeral markings provides a useful starting point for studies of these transient features and their implications for cataclysmal deposition. There is no doubt that a great variety of organisms have left behind them evidences of moving and feeding behaviour which are often beautifully preserved for scientific investigation. Whereas most studies of trace fossils attempt to use modern analogues to interpret past environments and ecosystems, there seems to be ample scope for innovative investigation. For example, Brand (22) has used evidence from vertebrate footprints to challenge the conventional view that the Coconino Sandstone exposed in the Grand Canyon was formed by aeolian deposition. The writer (23) has studied limulid trace fossils in the Bude Formation of south-west England and concluded that a catastrophic scenario is far more appropriate than the previously-held consensus that the assemblage represents a "sea-level lake community".

DIAGENETIC AND POST-DEPOSITIONAL PROCESSES

If sedimentation is rapid, compaction and dewatering of sediments must take place much faster than is customarily thought. Contemporaneous igneous activity releases volcanic fluids, particularly siliceous fluids, which help to cement the particles together. Other waters carrying calcium carbonate in solution are circulated by convection currents associated with hot intrusions, and these waters provide cementation with calcite. In some cases, such cementation can be proved to have taken place rapidly - as in coal balls. Similar reasoning leads to the conclusion that iron-carrying solutions were able to produce ironstones of varying kinds soon after sediment deposition. Rapid cementation and preservation of fish tissues in a phosphate-rich matrix is reported for Brazilian fishes (24).

Post-depositional deformation may occur while the sediments are still only partially lithified. It is quite possible that soft-sediment deformation over short timescales rather than consolidated rock deformation over long timescales (creep) is the norm in mountain belts.

This tectonically-controlled rock cycle opens the door for a fresh look at metamorphic processes. These are traditionally viewed as taking place over vast ages of time, primarily because of the Huttonian constraints on temperature and pressure changes. However, tectonic blocks may be dropped deep down into the Earth's crust, allowing deformation under high pressures, contact with hot rocks, and convective movements of superheated water (carried down with the tectonic block). Since water facilitates most geochemical changes, there are many possibilities here for reinterpreting metamorphic episodes. The timescales in metamorphic petrology are not determined primarily by rates of reactions, which can be studied over short periods in petrology laboratories. Rather, the timescales are associated with interpretations of slow changes of pressure and temperature, which are not part of this new rock cycle.

This view of rapid vertical movements of crustal blocks also provides a framework for reinterpreting both the processes of mountain-building and the formation of extensive overthrusts. The role of crustal block movements in the creation of mountain belts warrants serious investigation.

Many nappes are devoid of roots and their formation is a mystery within geology dominated by Lyellian uniformitarianism. A catastrophist geology, incorporating rapid vertical movements of tectonic blocks, does not have these problems. Gravity sliding of nappes, with water lubrication to explain the undisturbed nature of the thrust planes (25), seems to provide a feasible explanation of their origin.

Butler's review (26) of the subject area acknowledges major problems with conventional views, but points out important evidence that nappes are tectonically emplaced, and were not deposited in their current positions. Much diluvialist thinking has neglected this evidence, concentrating on the character of the contact planes at the expense of the evidence taken as a whole. The writer's view is that nappes do exist and are best explained using catastrophic mechanisms.

SUMMARY

A new rock cycle is proposed, in which tectonic processes control the formation, erosion, deposition and alteration of crustal materials. This rock cycle is inherently catastrophic, demanding short time-scales for geologic activity. Many of the concepts employed (tectonic blocks, fault-bounded sedimentary basins, synsedimentary faulting, diapiric rise of acid rocks, etc) are familiar to geologists today, but here they are given a more prominent role. Other concepts are incorporated which are not recognised by contemporary geologists (rapid rise of diapirs, phreatic stripping, cyclicity as an evidence of tectonic control, rapid metamorphic episodes, catastrophic overthrusting, etc). Nevertheless, within the tectonic framework that has been described, these concepts show coherence and possess considerable explanatory power.

If catastrophic geology is to develop as a science, it must show evidence of being able to handle field data in an orderly and systematic way. It is hoped that the tectonically--controlled rock cycle will assist this development.

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DISCUSSION

Mr. Tyler takes an innovative approach to the "rock cycle" explaining it in terms of catastrophic tectonics and processes which can be understood to proceed from catastrophic tectonics. This pioneering study will no doubt stimulate interest in exploring the implications for plutonism, metamorphism, erosion, sedimentation and lithification. The author displays his wide experience with the subjects being discussed. The notion of convective cooling of plutons is central to tectonically induced diapiric processes. It would merit a separate paper. The concept of catastrophic erosion by phreatic stripping is a valuable addition to catastrophist theory. It should be investigated in a later study. Perhaps the best way to test the theory of the rock cycle suggested by Mr. Tyler would be with specific application to a region of the earth's crust. I look forward to application of the theory presented in this paper.

Steven A. Austin, Ph.D.
Santee, California

This paper by Mr. Tyler includes many interesting and important discussions and observations. My questions regarding the author's paper are:

1) Does the equation on diapirism (Stoke's Law) really work for melted lava or solid rocks in the earth's crust?

2) What about the possibility that the equation is only valid for small scale experiments, in the laboratory, in liquid media?

Mats Molen, M.S.
Umea, Sweden

A delusion of almost two centuries' standing is struck here at its roots. The enormity of the Huttonian error is just beginning to dawn on contemporary geologists. This is witnessed by allusions to "event" or "spasmodic" occurrences in geology scattered through the more recent literature although all the while interspersed with vitriolic remarks for those who are committed to the construction of a scientific framework of biblical earth history. In "organizing ideas into a coherent whole" the author has built his case on the revealed facts about the former conditions on our planet and the changes triggered off by the Flood. He has thus succeeded in an area of model-building where many luminaries of geology have failed. The evidence for the rapid cementation of sediments can be amplified by referring to fossils, and the ensuing problem for uniformitarian geology may be even more acute than creationists are aware of. The lithification of buried organisms, i.e. the change from organic to inorganic compounds without loss of form, has so far withstood all attempts at experimental repetition and is likely to continue outside the realm of phenomena that are scientifically explicable.

Joachim Scheven, Ph.D.
Hagen, Germany

Mr. Tyler's paper is an exciting and valuable contribution to flood geology. Hutton's rock cycle with its explicit requirements of "deep time" has persisted in geology for over two hundred years — virtually without challenge. The author's tectonically-controlled rock cycle may well be the needed challenge to Huttonian geology from catastrophist geology.

Upper mantle viscosity seems to be too high to allow deformation or motion to occur on the time scales necessary (month/days) for this model (isostatic rebound is thought to take 1000's to 10's of thousands of years.) How does Mr. Tyler explain the necessary motions at depth?

If basic/intermediate rocks & acidic rocks have distinct origins, how does one account for the continuous range of igneous rock composition? Would not this model predict a rarity (if not an absence) of rocks between intermediate & acidic composition? Are the predictions borne out be evidence?

Why did such a cycle only occur during one episode in earth history? What causes are necessary and sufficient to initiate it? (i.e. what would have initiated the partial melting of the mantle and crustal rocks?) What caused the cycle to stop? (i.e. what terminated the partial melting?)

Kurt P. Wise, Ph.D.
Bryan, Tennessee

CLOSURE

Dr. Austin is thanked for his comments. The tectonically-controlled rock cycle is intended to provide a framework for interpreting field evidences and, if it does not lead to further papers on the subjects of convective cooling of plutons, phreatic stripping and regional case studies, I will not have achieved my objectives. In geological circles, one often hears people speaking of the impact of new ways of thinking: "We didn't see it because we were not looking for it— but now we're thinking in this new way, we have no difficulty finding examples of it in the field!" This my own experience with the tectonically-controlled rock cycle, and it is my hope that many others will find it useful.

Mr. Molen's specific questions relate to my use of Stokes' Law to describe the flow of magmas though the solid crust of the Earth. Insofar as the crustal rocks have a measurable viscosity, the equation can be applied. The main doubts concern (a) the magnitude of the dynamic viscosity of the crustal rocks, and (b) the onset of brittle fracture and fault movements as the diapir approaches the Earth's surface. The value of viscosity I have used is non-controversial among the geological community, so the case for catastrophism cannot be lightly dismissed. The second question is one which must be considered at quite a different level. It concerns the application of a physical law to a situation where it has not been proved in laboratory experiments. The sciences of Physics and Chemistry have developed with the assumption that laws which are discovered may be applied generally to physical and chemical phenomena. It is wise to be open to the possibility that physical laws may be inapplicable outside the context of their proven validity but, in any particular case, experimental evidence should be sought to provide some test of the theory.

I am grateful for Dr. Scheven's remarks. We live at an exciting time when catastrophic ideas are making headway in the geological literature. However, most thinking continues to be locked into traditional timescales and catastrophic events are perceived as intermittent and fragmentary punctuations of the general calm. Consequently, there is little opportunity for catastrophism to provide a unifying framework for geological interpretations. This is one intellectual reason why resistance to flood geology concepts continues to be so strong even among neo-catastrophists. Only by discarding the rigid timescale for the formation of the different strata can justice be done to the field evidences, and only by anchoring our thinking to the biblical framework of history can we avoid floundering about in a sea of chaotic scenarios.

Dr. Wise's comments on the significance of this challenge to Huttonian geology are encouraging. So much of geological thinking is paradigm-dependent, and yet this is rarely appreciated without the advantages of viable alternative frameworks for theoretical ideas. I am sure this is true of upper mantle viscosity estimates, where the values associated with the various parameters do not appear to be independent of conventional timescales. There are various ways of responding to the point that upper mantle viscosities seem to be too high. The vertical movements of crustal plates, proposed in the tectonically-controlled rock cycle commits itself to any mechanisms of mountain building and plutonic activity. The tectonic framework is one which has been inferred from the field evidences: mapping of major vertical movements, analysis of sediments adjacent to the fault boundaries produced during movement of the tectonic blocks, the character of inter-block sediments, seismic reflection data, etc. Nevertheless, it has been argued that one mechanism for the rapid vertical movements of crustal rocks is diapirism, and this mechanism has no requirement for unusual mantle viscosities.

Regarding the prediction that rocks of intermediate composition are less prevalent than basic and acidic rocks, this is a fair reflection of the field data with which I am familiar.

The remaining questions are concerned with the causes of catastrophism, which are undoubtedly of great interest. However, it is my argument that it is not necessary to identify specific causes in order to work on a science of catastrophic processes. I am confident that Biblical history gives us the framework within which we can make progress, but there would appear to be considerable scope for alternative ideas on the technical details of cause and effect in global catastrophes.

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