"The climatic factor in landform development is by no means as clear cut and simple as was once thought and is certainly not of over-riding importance over at least half of the world's land surface." **[Twidale & Lageat, 1994]**

Discuss, with particular reference to karst landsystems.

The current geomorphological discourse surrounding landform development often places the influence of climate commensurate to lithology and structure. Scientific thought has evolved over the last century to incorporate complexity into the formation argument. An abundance of literature has arisen to signify climate is not as singly influential as was once thought; indeed its importance has been proven to be relative to scale, with variability amidst the micro and macro scales. The core of this essay lies in weighing up the relative importances of climate and geology in the formations of karst landscape, juxtaposing the solutional with the structural. Distinctive Karst are of critical geomorphological importance, their changeable carbonate origins being temporally and visually recordable. In studying the evolution of our understanding of karst, one attempts to flesh out the argument proposed by Twidale & Lageat's quote. It is, however, important throughout that one does not regard the rise of tectonic influence as inversely proportional to that of climatic influence. Climate remains, and always has done, a significant influencer upon landscape. Thus a sensible conclusion, and one which this essay works towards, is that both climate and structure work together as components in a much greater formational process.

Climatic geomorphology is concerned "with the relationship between climate and the efficiency of geomorphological processes, and the way in which this relationship leads to characteristic landform assemblages in different climatic environments." *(Hancock & Skinner, 2007)* Throughout the early 20th Century, the geographical discourse concerning landform development hinged firmly upon a post-Davisian theory, with climate being the single generator of landscape. The genesis of such a discourse predated to Davis' early writings which elucidated a deep, entwined nature of specific aspects in the geographic cycle with the climatic regimes under which they were formed. In diagnosing the existence of unique, arid and glacial cycles, 'climatic accidents' as he would later name them, Davis deduced that all process was dependent upon climate. As Peltier propounds: "this was [pure] corollary to his classic formula: form is the result of the influence of structure plus process plus stage." The scientific appeal of his theory was its unified theme, one that linked "climate, land surface, soil [and] vegetation" on a global scale. Theories arose based upon its principals amidst a bout of European empiricism. With Penck, Thorbecke and Budel at the fore, it was theorised that "various climatic factors, and particularly temperature, precipitation and wind induced the operation of specific processes" that together formed unique, global morphogenetic systems. The interactions of these climatic factors then produced morphogenetic regions, "landforms and landform assemblages that were typical of and peculiar to particular climatic regime[s]" (Twidale & Lageat, 1995). Their climatic morphogenesis was supposedly evident in about 50% of the global landscape within the "desert, glacial and possibly also the periglacial or nival" regions. Penck had indeed, by 1909, described each of these as distinct in their climates, hydrologies and geomorphology. The problem was that, such climatically-zonal morphogenetic regions subordinated the roles of structure and time in landscape evolution (suggestive even, that climatic regions produced unique landforms *independent* of time and structure).

By the latter end of the century the classical approach became increasingly questioned. It was in 1969, the year of the lunar landing, that Stoddart, in his scathing criticism of the existent discourse, would renew discussions upon the need to investigate "the influence of climate relative to other factors such as lithology and structure at different scales."

Similarly Twidale and Lageat would raise a spatial-scalar question: if climatic morphogenesis was only applicable to half the globe, what "of the remaining 50% of the land areas, [those] *not* embraced and shaped by modern glacial, nival or desert systems?" The critique was based upon the premise that if these "other" morphoclimatic zones produce landforms not as immediately climate-determined, then surely there must too be "other" influencing factors. A quote from Twidale and Lageat's work forms the basis of this essay and in contextualising it, one can begin to formulate answers. The Critique concludes: "In all morphoclimatic regions the effects of geological structure are [also] significant, even in those regions where climate exerts a strong influence on landform development." Such a trajectory, in a sense, coalesces the school of Davisian thought with a post-Wegener discourse; it accounts for the influences of both exogenic climate *and* endogenic tectonism, aggregating them in the overall process that determines landform development.

Karst provides a relevant study into the "climatic-factor-significance" question. Indeed M.M Sweeting, having dusted her sandals of Jamaican Karst, would write a statement strongly adherent to the ongoing debate: "we know that though climatic differences affect karst processes, the correlations between climate and landform are not as simple as we once supposed" - *by no means as clear cut (Sweeting: 1958).* Within Karst landscape the dual processes of climate and geology are identifiable. The term karstland "denotes a region of massive limestone or dolomite where the evolution of the relief is dependent upon chemical erosion - solution - as the dominant process in land form development" and where, as a result, surface drainage becomes diverted into underground channels. *(White, W.B: 1988) (*Karst is indeed German for the Slovene word "kras" meaning a bleak, waterless place; the classic Dinaric Karst region originating near Trieste.) As Ford & Williams reveal, karst landscapes are "characterised by sinking streams, caves, enclosed depressions, fluted rock outcrops and large springs." Large areas of the ice-free continental area of the Earth are underlain by Karst developed on soluble, carbonate rocks such as limestone, marble and gypsum. Limestone is a rock dominated by the mineral calcite (CaCO3), while the other widespread carbonate rock is dolomite (CaMg(CO3)2).

The solutional process is pivotal in the formation of karstic landscapes. The incorporation of dissolved atmospheric CO2 into water during precipitation forms a dilute carbonic acid. Calcium carbonate, CaCO3, which forms much of limestone, dissolves in the presence of carbonic acid to yield the more soluble calcium bicarbonate, Ca(HCO3)2, which is much more readily transported away in solution. The amount of CO2 dissolved into an aqueous solution is controlled by temperature and the atmospheric concentration of the gas. In 1959, Jean Corbel inferred that temperature acted as a solution control through its inverse effect on the solubility of carbon dioxide, such that CO2 saturation concentration at 0°C is twice that of 20°C. Just as the lower the temperature is, the more dissolution; the greater the atmospheric concentration, the greater the dissolution of CO2.

Solution of CO_2 in water: (CO2 (g) + H2O (l) = H2CO3 (aq)

Limestone dissolution by carbonic acid: CaCO3(s) + H2CO3(aq) = Ca2+ (aq) + $2HCO3^-$ (aq)

Dissolution is often conceptualised as an interaction between geochemical and hydrological subsystems. The main source of natural energy is provided climatically and via the hydrological cycle to drive the evolution of karst; water being the solvent that dissolves karst rock and then carries it away in solution. Geochemical processes then control the rate of dissolution (the transition of solid rock into solution-bound ions), which in a carbonate karst is dependent upon the strength of acidification by dissolved carbon dioxide during its passage through the atmosphere and soil layer before reaching the limestone. The soil layer is significant as "the concentration of CO_2 can be 20-30 times higher than that in the atmosphere" due to biogenic processes - the respiration of plant life and bacteria and the inflating influences of decomposition (which also release chelating agents to aid the solution of stable cations) (Bland & Rolls: 1998)

If solution is regarded as a climate-determined, the structure and lithology of limestone can be regarded as the significant non-climatic determinants of Karst. For distinct karst landforms to evolve, there must be differential erosion rates within the landscape. If uniform lowering were to occur, that is to say, if limestone erosion takes place predominantly in the upper soil, no karstification occurs and the landscape simply retains its tectonically-determined, original form. Such uniform erosion in karst is evident in soft halites and chalks (the Cretaceous chalklands of Britain an example), in which such universal dissolution limits the formation of karstic features. Uniform erosion is likely if rainwater is able to penetrate freely between the individual grains of the limestone (*primary porosity)* as solution will be diffuse and spread equally over the outcrop of the rock. However, if the intact limestone has negligible permeability itself, then the only mode of entry for water is via secondary fissures such as joints and faults (*secondary porosity).* Solutional erosion becomes concentrated selectively at lines of weakness. The most important structural characteristic of karst is that these permeabilities change with time; young limestones such as chalk have high intergranular porosity that later evolve into fracture porosities. When a carbonate sediment is formed it acquires its fabric selective primary porosity. As Ford & Williams infer: "these primary voids are somewhat diminished during lithification and diagenesis (compression and compaction)." Later chemical diagenetic processes such as dolomitisation result in the acquisition of *secondary porosity*; which is considerably enhanced by karst solution along penetrable fissures by circulating groundwaters. This evolution between the porosities is significant in producing the lateral variations and differences in solutional karst landforms. The development of karst landscapes in the region of Meghalaya, India is closely related to lithological characteristics of rocks and is controlled by many natural conditions in particular lithology, structure of rocks, climate, height of the water table and nature of drainage as well as biogenic process. The southern part of the plateau being mainly composed of Cretaceous Tertiary sedimentary rocks contains numerous faults and folds. The uplift of the plateau in the late Tertiary period gave rise to a complex multi cyclic landscape, a suggestion that morphotectonics can often hold precedence over climate in certain karst formations.

One such occasion in which internal lithology supercedes climate is held in the study of micrite-sparite cement. Limestones are formed by the accumulation of carbonate sediments on the sea bed, their characters being determined by the depositional environment and subsequent diagenetic physical and chemical alterations. Limestones are composed of distinct fragments (allochems) held together by a calcite cement that is either fine-grained, such that it is micrite, or coarsely crystalline, such that it is sparite. The lithologies of these two cements are strong determinants in the formation of karst landscapes. Evidenced from lengthy studies of the Pennsylvanian limestones of Ordovician age, was the fact that: the more micrite present in a limestone the greater the size of cave passage. Meanwhile the greater the presence of sparite, the lesser the cave passage per unit of rock strata. This seemingly simplistic model is further evidenced in Northwest Yorkshire's karst in which deep vertical trenches have been excavated in sparite whilst micrite-rich limestones have coincided with broader, boulder-strewn valley floors. *(Smithson, Addison & Atkinson 2008)*

Karst landforms, in the classical, uninterrupted sense, progress through a series of distinctive stages. The primary formation of karst is visible in *Karren*, the micro-solutional features that develop when aggressive carbonic waters, charged with solutional potential, etch grooves into limestone. Lithological properties are significant in this process, karren often forming only through homogenous and fine grained rock. Dreybrodt goes so far as to suggest "variations in lithology, hydraulic gradient and the duration of the karst denudation outweigh climatic control." The secondary formation is transitional, with juvenile karren evolving into deep depressions known as dolines (sometimes 1000m in diameter). The process occurs when rainwater further percolates through the karren-fissured limestone, enlargening through solution the uppermost fissures and bedding partings of the rock. This process of concentrated erosion often holds no expression at the surface. Eventually however the ground subsides, catastrophically or imperceptibly, into the void beneath to produce a declivity at the surface. When closed depressions dominate a karst landscape it is an indication that the 'logic' of the landscape has shifted underground; that rivers that once carried waters and dissolved loads to the sea are now in caves within the limestone.

The third formation, that of cave systems, are integral features of karstified limestones, their evolution being both a cause and a result of surface karstification. Caves are the "conduits for the transmission of underground water, from inputs (stream sinks) to outputs at springs (resurgences)", essentially the subterranean equivalents of surface stream networks *(Ford & Williams, 2007).* Caves only develop, much like their karren and doline predecessors, because a limestone with low primary porosity, confines acidic waters to secondary openings; faults and bedding planes. The localised solution creates large conduits, with bedding planes and their extensive, continuous seams of weakness often catalysing the progressive drainage of water underground. The great range of dramatic features in cave systems are not all the result of limestone solution, mechanical abrasion by pebbles and stones carried in underground streams, and mechanical subsidence when caves enlarge so that the roof may collapse, contribute to the diversity of cave forms that exist. Occasionally tectonic subsidence creates a palaeokarst, a karst landscape "hyrdologically decoupled from the contemporary system" but occasionally exhumed and reintegrated Caves suggest that karstic features are inherently dependent upon lithology and structure, most notably in primary and secondary porosities, however climate is not redundant and remains significant in a hydrological and solutional sense. Temperature alone is pivotal in influencing the water balance, the rate of chemical reactions and the biochemical processes in carbonation. One could argue that, if the greatest limestone solution in the world occurs where it is wettest, surely precipitation overrides temperature in significant. Yet again however, *both* are climatically rooted.

The proliferation in morphogenetic cartography at the latter stages of the 20th Century are somewhat inapplicable to Karst. Indeed, Twidale & Lageat observed the karstic rock towers of the tropics as strong illustrators in "the problems of climatic interpretation; for they not only evolve in a wide range of climatic environments but also in bedrocks additional to limestone." Karst, seeming to transcend both species and place, debunk the idea that climate can produce unique, spatially independent landscapes. Nevertheless, Karst has been optimistically cast into its own three broad morphoclimatic zones; the tropical, the temperate and the arid/alpine. At the extremities, arid karst is poorly formed because little water for solution is present; the existent water table, deep; and the vegetation and carbonic soils scarce. Furthermore erosion is at a minimum in the arid environment where, irrespective of CO2 availability, runoff is negligible. It is evident that the climatic influence thus far, is significant, especially in relation to the presence of water and CO2. Within the alpine regions, even though CO_2 is more soluble in its cold water, the minimal bacterial decay, non-existent biological CO_2 and slow reaction rates create negligible and rare karst formations. Similarly and most significantly, alpine regions alike the arid, are deficient in liquid water, key in the solution-weathering process. Pseudokarst, one that originates from non-solutional processes is however present in alpine regions. Limestone, dolomite and gypsum outcrop over 1,200,000 square kilometres in Canada. Much of the country was repeatedly glaciated by alpine glaciers and continental ice sheets during the Quaternary, with half of it permafrost today. The interrelationships between glaciers and the karst systems are complex, manifesting themselves predominantly in erasure by glacial scour. The scour impacts chiefly upon karren. Further glacial interruptions involve the dissection of karstic cave systems, the infilling of dolines with glacial detritus and the shielding of soluble bedrocks from postglacial dissolution. "Positive glacial input is seen in the induction of interstatal dissolution by deep injection of groundwaters during glacial recession and isostatic rebound" *(Ford, D: 2003)*. The Somersettian Cheddar Gorges reveal a relict karst, dating from the Pleistocene glaciations of the past that created limestone landforms, wholly independent of solution. Cheddar, rather, was the result of surface stream incision of frozen, and thus impermeable, rocks. Similarly the limestone pavements - bare rock surfaces - of the Yorkshire Dales are relict representatives of the stripping by ice of upper beds of limestone previously weakened by solutional erosion of its bedding planes.

If one agrees, as Twidale & Lageat do, that "differences in carbon dioxide availability and in temperature are the ultimate determinants of the solution process", then tropical karst evidently hold the most solution and thus the most mature and distinctive karst. There is a general trend towards higher soil carbon dioxide levels with warmer climates. The thicker, more biologically active soils are created by organic acids and plant decay, whilst the abundant atmospheric hydrology provide the acids with an aqueous host. In 1998 Bland & Rolls found that the partial CO2 pressure of the tropics could be "as much as 11% compared to the 0.1-3.5% temperate average". Tower karst, widely regarded as the defining features of humid tropical karst, (abundant in the Antilles, monsoonal northern Australia and southeast Asia) are formed as a result of strong solutional processes of past and present climates. Southern China is a case in point, richly-soiled with a South East Asian monsoon and great fluvio-karstic rivers, such that tower karsts of 200m+ are present. Yet China, like Southern Europe has been subjected to neotectonism, "the proximity of the Chinese karst areas to Tibet and the Himalayas...probably of greater significance than the nearness of the classical karst and Dalmatia to the Alps." *(Sweeting, M.M. 1990)* Again over the Quaternary history. climate is influential in karst formation, but not without morphotectonics weighing up commensurately. Omitted from the opening of this paragraph is the end of Twidale & Lageat's quote, one which firmly stated that the effects of such differences in carbon dioxide availability are locally "modified by rock, soil, topographical, hydrological and biological factors." Indeed perhaps the tectonic process of internal stress, strain and fracture, of rock, soil and topography are as significant as climate in landform development.

To question whether processes internal to the earth are as significant (if not more) than climatic influence requires an observation of a region with a similar climate but differing lithology and vice versa; one with similar lithology but differing climate. Puerto Rico, an island of the tropics with Tertiary age limestone outcropping at its north and south coasts reveals the significance of climate. Although Puerto Rican limestone is lithologically and structurally similar, the precipitation and thus solutional profiles of the north and south localities differ. Annual rainfall in the south oscillates around 900mm whereas in the north it rises up to 4000mm. "Cone karst, large cave systems and deep closed depressions dominate the northern landscape", whilst the south only has closed depressions and a scattering of small caves. *(Frank, E et. al: 1998)* The correlation between precipitation with its solutional potential and karst development is evident and suggests climate is of overriding importance in karst development. Furthermore, the north is structurally-deficient in the joints and fractures required for secondary porosity, whereas the south is structurally-abundant, yet it remains that the North of Puerto Rico is deep karst region. A differing example is M.M Sweeting's Jamaican karst. The lithology of the island is variable, although each outcrop predates to the Eocene-Miocene age. Near to the coast, the Montpellier limestones are chalky, poorly-jointed and have a high primary permeability, that renders their karstic features shallow and subdued, dominated by gentle slopes and wide hollows. Further inland, the crystalline, well-jointed white limestones, deep cockpits and karstic hills predominate. The centre of Jamaica, underlain by yellow limestones, intermediate between the other two and thus exhibit landforms commensurately mixed in feature. This, far from the Puerto Rican study, would suggest lithology and structure, the binding geology of a landscape were the key determinants and sole cause of karst. However, and as Sweeting discovered, rainfall inland was twice that at the coast, temperatures, soils and vegetations also varied. Thus if precipitation was most deficient at the coast, then its poor karstic features are again attributable to climatic influence. Nevertheless, and reiterated again within this essay, Sweeting revealed that "the correlations between climate and landform are not as simple as we once supposed." (*The Karstlands of Jamaica: 1958)*

An appreciation of scale is important in an evaluation of the "climatic influence" and its significance in landscape development. At the macro scale, the classical approach related specific morphogenetic systems with specific morphogenetic regions. Yet this theory perhaps applied to only half the Earth's surface, the other 50%(Karst included) fitting rather more ambiguously. The overriding support of climatic influence at the beginning of the 20th Century was grounded on concepts within regions, that were themselves inherently unstable. The morphogenetic system and its glacial, arid and nival regions are historically prone to collapse and sudden crises of glacial and interglacial proportions. Something so volatile cannot alone determine the Earth's landscapes in its entirety. Siding with the Twidale's, the Lageat's and the Stoddard's, one respects"the influences of climate" but "relative to other factors such as lithology and structure at different scales." The latter two words are significant. What is evident, is that the relative importance of climate varies with the scale of analysis. It is approximately equal with lithology at the micro-scale, the Jamaica scale; of minor importance at the meso-scale; and is dominant at the macro-scale - dominant in global Karst as the originator of the solutional process. The complexity of the question Twidale & Lageat raised is evident once scale, amongst all the other variable, is taken into account. Even more so by the facet that "passing from the micro to the macro-scale, there is a decrease in the significance of moderate climatic events and an increase in the importance of events of greater magnitude" *(Morgan, R.P.C, 1973)*. Landscapes embrace chaos and complexity. Amidst its intricacies and feedbacks "climatic factors are important in inducing the operations of those processes [finding] clear expression in landform" It does however "constitute but one of several factors that determine the shape of the Earth's surface." (*Twidale & Lageat, 1994)*. Lithology, climate and structure coalesce in their creation of landscapes, most notably in karst. Hanging up one's sandals and retiring to the horizon, as Sweeting once did, it is clear that the correlations between climate and landform are indeed, not as simple as was once supposed.

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