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INFLUENCE OF CLIMATE AND RELIEF ON COMPOSITIONS OF SANDS RELEASED AT SOURCE AREAS

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ABSTRACT

Mass balance requires that any study of the relation between provenance and detrital sediments must take into account all the processes, such as climatic and biochemical, that contribute to any modification of the parent material at the beginning of a sedimentary cycle. In addition, exceptions to the relationship between tectonic setting and sandstone composition may be traced to climatic processes. Despite an enormous amount of research on atomic level dissolution phenomenon, little work has been done to characterize the sandy residue of weathering. Available modal data, albeit meagre, show that the mineralogic composition of the sand size fraction of soils is similar to that of first order stream sands. This indicates that pedogenic processes largely control the composition of first cycle sands derived from similar bedrocks. Further, the data also suggest that modal compositions of first cycle sands are broadly indicative of both parent rock type and climate. Recalculation of data from only one available study indicates that steep hill slopes exceeding the angle of repose can obscure climatic effects on first cycle sand composition. One may infer that slope angle, which controls the duration of pedogenic processes, not relief, has more significance in overcoming climatic effects. Evaluation of the relative importance of dissolution and disintegration of minerals, especially polycrystal-

G. G. Zuffa (ed.), Provenance of Arenites, 1–18.

line quartz, is difficult because lattice dislocation increases solubility as well as brittle strength. Given the extreme paucity of data from controlled studies on the effects of climate and relief and the seemingly significant compositional diversity brought about by pedogenic processes, we must conclude that this is a potential area of much fruitful research.

INTRODUCTION

It is desirable to define provenance at the onset of this "Institute" so that all of us can use the same vocabulary, and more importantly, focus on the concept. The word provenance has been derived from the French word _provenir_ and the Latin word _proveniens_ meaning origin or the place where produced. However, in sedimentary petrology, provenance refers specifically to the nature, composition, identity and dimensions of source rocks, relief and climate in the source area, and to some extent includes a transportation factor which is mostly understood to convey a sense of the distance and rigour of transport of sediments until deposition (Suttner, 1974). Thus one can write:

provenance = f (source rock, relief, climate, transportation)

The objective of all provenance studies should be to work out the quantitative paleogeology of a part of the earth's crust. Sedimentary facies and basin analysis, aided by seismic stratigraphy, provide paleogeographic reconstructions; and, we may infer the relative positions of land and water, the shorelines, perhaps the width of the shelf, and also the relative locations of some land features such as mountains, river valleys, swamps, etc. with respect to the location of the main basin of deposition. Detrital remanent magnetic studies of sediments can provide paleolatitude. Structural analysis of folded units may, but not necessarily, provide some information of the tectonic setting of the depositional basin. However, only provenance studies can bring all results together to provide a broad picture of paleogeology. We strive to infer not only the location of a mountain shedding sediments or to infer the rocks that made up the mountain, but also to find the relative proportions of these rocks as the highlands were eroded to the base level. The task is not easy and it may take years before tangible results are obtained from research with such an aim. After all, "the question of provenance is one of the most difficult the sedimentary petrographer is called on to solve" (Pettijohn et al., 1972).

PROVENANCE

It is now common knowledge that the plate tectonic regime of a highland, i.e. of an area which can and does shed sediments, controls the petrologic assemblage of the highlands (Dickinson, 1972, 1980). The rate of erosion of the highland is controlled by relief and climate in the area; uplift and erosion gradually unroof the rocks and eventually expose those in the core of the highland. Thus exposure and the duration of exposure of a rock type in the source area is also a function of relief and climate which provide a certain degree of topographic maturity to a highland. The effect can be understood best from an example. Both the Alps in Europe and the Appalachians in North America are products of continent-continent collisions. However, because of the difference in degrees of unroofing, and because of the difference in their topographic maturities, these two mountain chains now shed sands of slightly different compositions. Exposure age and the plate tectonic regime of highlands also control to a large extent the relief and the rigour of transport. Usually, rigour of transport is often associated with distance of transport which may be dependent on tectonic setting. For example, slow moving big rivers usually drain large continental blocks and flow on passive trailing edges of continents. In contrast, rapidly flowing short streams drain mobile belts in active continental margins (Potter, 1978). However, there are exceptions. For example, relatively short rapidly flowing streams drain the trailing edge of the continental block of southern India. Overall, it appears that the variables source rock, relief and transport are functions of plate tectonic regimes and exposure ages of the highlands.

Contradiction

Climate of an area is, however, independent of any direct tectonic control. The more important parameters in rock weathering, viz. rainfall and temperature are dependent on latitude, elevation and orographic effects, and on land-water distribution. Rainfall and temperature have a profound effect on the rate of rock-weathering and, as pointed out earlier, determine the rate of erosion to a large extent. Rainfall and temperature also control, to a large extent, the growth of vegetation and the attendant biomass in a highland area, and thus significantly contribute to biochemical alteration of original rock material. Many exceptions to the now well established relationship between tectonic settings and sandstone composition (e.g. Dickinson et al., 1983) may be traced to the vagaries of climate in the source areas (Mack, 1984).

Genesis of sediments begins with regolith and/or soil formation on a bedrock. The composition of the bedrock is controlled primarily by plate tectonics; however, the processes of alteration of the bedrock material are driven primarily by climate. In this paper we shall (i) try to examine the control of climate (rainfall + temperature) on the composition of sand released by common source rocks, (ii) briefly comment on our ignorance about the effect of relief, and (iii) try to identify areas of potential research in provenance interpretation.

COMPOSITIONS OF MODERN SANDS

The only way to evaluate the control of climate on the composition of sands released at source areas is to adopt a sampling technique which keeps all other variables constant. Therefore, in a desirable sampling technique one would try to keep the source rock, relief, and transport as invariable as possible and sample modern sands from different climatic zones. Although many writers have characterized modern sands derived from different tectonic regimes and rock associations in different climatic zones, except for the Indiana group no one has adopted the sampling plan described above. Therefore, we shall initially consider only the Indiana data (Suttner et al., 1981; Basu, 1976; Young, 1975; Darnell, 1974).

One important result of the Indiana group indicates that the modal compositions of the sand size fraction of hill slope soils and regolith are very similar to that of the first order streams draining the same hills where slope angle < angle of repose (fig. 1). Data were collected separately for plutonic igneous, i.e. granitic bedrocks, and high rank metamorphic bedrocks, i.e. high grade schists

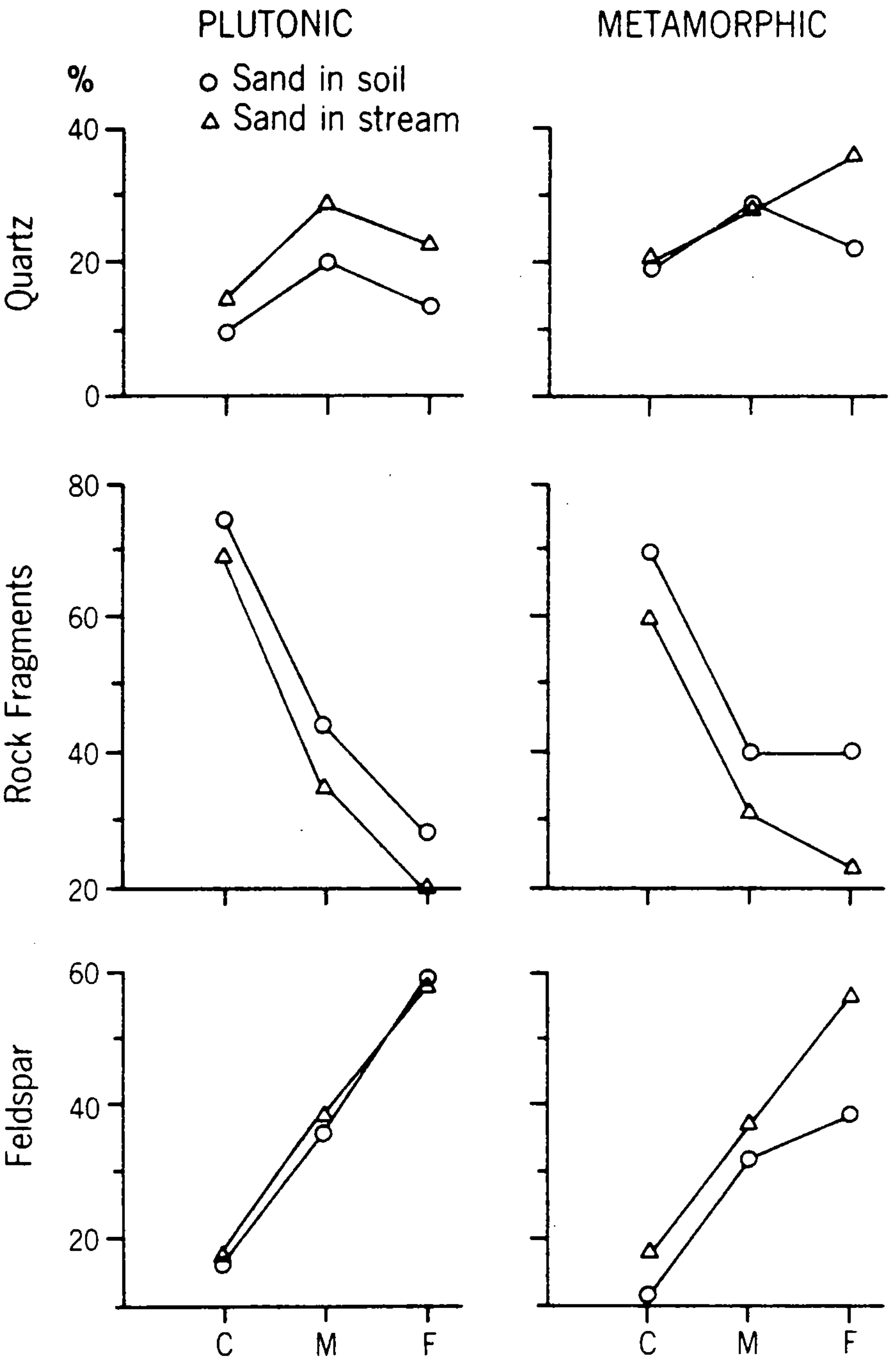

Fig. 1. Modal compositions of coarse (c), medium (m) and fine (f) sand from hillslope soils and adjacent streams draining either plutonic igneous or metamorphic bedrocks (after Suttner et al., 1981). Note the remarkable similarity between the compositions of sands from two sub-environments.

and gneisses, from the hills in relatively arid northwestern U.S.A. (Table 1). A major implication of this result is that the modal composition of the initial sand supply to the sedimentary system is

Table 1. Recalculated abundance (%) of quartz, rock fragment, and feldspar in soils and associated first order stream sands in coarse, medium, and fine sand size fractions. All samples are from northwestern United States. (Suttner et al., 1981; Basu, 1976; Young, 1975; Darnell, 1974).

	Grain Size		
	Coarse	Medium	Fine
I. Soils			
(a) High Rank Metamorphic Source Rocks			
Quartz	19	28	22
Rock Fragment	70	40	40
Feldspar	11	32	38
(b) Plutonic Igneous Source Rocks			
Quartz	9	20	13
Rock Fragment	75	44	28
Feldspar	16	36	59
II. Fluvial sands			
(a) High Rank Metamorphic Source Rocks			
Quartz	21	27	36
Rock Fragment	60	32	23
Feldspar	19	31	41
(b) Plutonic Igneous Source Rocks			
Quartz	14	28	23
Rock Fragment	69	35	20
Feldspar	17	37	57

determined by the degree of weathering in the soil zone for any given bedrock (Suttner et al., 1981). Comparable data are not yet available for other climatic zones. It is quite likely that the proportion of clay relative to the sand fraction in the regolith or soil developed in hot humid climate would be much higher. However, there is no evidence yet to show that the relationship between modal compositions of sand sized fractions of soils and adjacent stream sediments would be any different from that found in northwestern U.S.A.

The second result of the Indiana group shows that modal compositions of stream sands derived from similar parent rocks are controlled by climate, i.e. precipitation in the source area. The results, strictly limited to medium sand size fraction (0.25-0.50 mm) to avoid size-composition effects, are good for common parent rocks, viz. plutonic igneous granites and metamorphic rocks i.e. schists, gneisses, and granulites (fig. 2; table 2).

Table 2. Average abundance of quartz, feldspar, and rock fragments in medium size sand (0.25-0.50 mm) from first order streams draining exclusively plutonic or metamorphic bedrock in humid and arid climates. The numbers in parenthesis denote one standard deviation.

Source		Daughter Sands(0.25-0.5 mm)		
Rock	Climate	Quartz %	Feldspar %	Rock Fragment %
Plutonic	Humid	60(5)	27(4)	13(3)
Plutonic	Arid	27(4)	39(4)	34(5)
Metamorphic	Humid	74(12)	6(6)	20(9)
Metamorphic	Arid	29(8)	3(3)	68(10)

Note that the Indiana group adopts the traditional point-counting technique and not the Gazzi-Dickinson method (Ingersoll et al., 1984; Zuffa, this volume). The population of rock fragments in the Indiana data effectively separates plutonic and metamorphic source rocks (fig. 2). If counted otherwise, we suspect, not only the parent rock distinction but also the

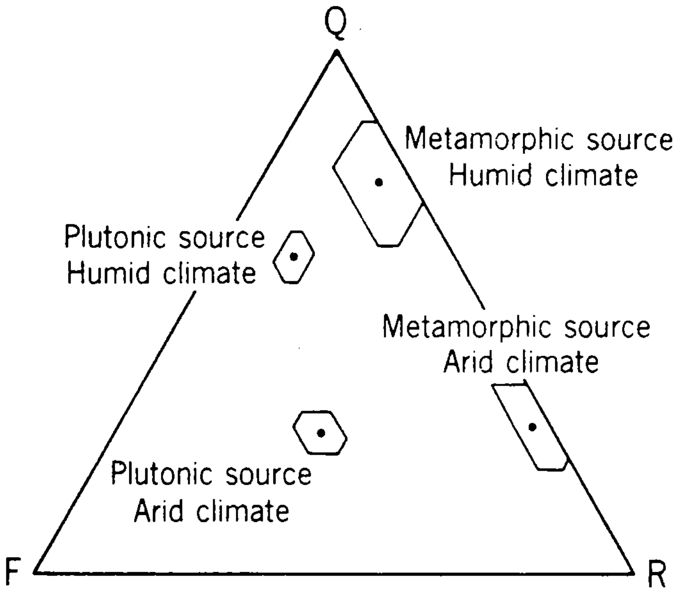

Fig. 2. Average compositions of medium sand-sized (0.25-0.50 mm) fraction of first cycle stream sand derived from plutonic igneous and metamorphic sources but produced under different climatic conditions are plotted in a standard QFR diagram (after Suttner et al., 1981). One standard errors on Q, F, and R are used to construct the error polygons around each average point (after Ingersoll and Suczek, 1979); actual scatter of the raw data plot in overlapping fields (Suttner et al., 1981; their fig. 1). Modal analyses were performed in the traditional fashion. Note that climate produces distinctive compositional effects on first cycle sediments. If counted according to the Gazzi-Dickinson method (Ingersoll et al., 1984) most of the distinctions seen on this plot would have been lost.

climatic distinction might be obliterated to a large extent.

Many scientists have investigated the chemistry of rock weathering induced by the biosphere, especially by plants. However, only one paper explicitly considers the effect of land plants on detrital mineralogy. Todd (1968) argued that depending upon the type of vegetation, the Na^+/H^+ and K^+/H^+ ratios in soil-waters could vary as much as to affect the relative stability of andesine and orthoclase. Todd (1968) showed that the nature of plants, rainfall and temperature determined if andesine would be more "weathered" than orthoclase, or *vice versa* in a soil horizon. Relative stability of K- and Na-feldspars were also invoked by Basu (1981) who argued that in well vegetated areas alteration of K-bearing minerals is faster than in areas without much vegetation because "potassium appears to move more quickly from the soil into the plant than do other common cations" (Paton, 1978). Therefore, before the advent of land plants, K-feldspars in pre-Silurian sediments should have had suffered less alteration than K-feldspars in post-Silurian sediments because of the added uptake of K^+ from soil-waters by the biomass of vascular plants in post-Silurian times. Although compilation of chemical data by Maynard et al. (1982) support the hypothesis, Graustein and Velbel (1981) disagree. Clearly, this is an open field and many new interesting research could be performed to evaluate the control of biochemical processes in determining the modal composition of sands.

On the other hand, a vast amount of geochemical research has been and is being done on the nature and the kinetics of reactions that lead to the dissolution of rock forming minerals and precipitation of new minerals in soil horizons (Nesbitt and Young, 1984). One area of very interesting research evaluates the role of newly formed minerals (e.g. kaolinite) in coating and mechanically protecting the original mineral (e.g. feldspar). Wollast (1967) in a now classic paper propounded this shielding idea. Since then many have tested it with dissolution kinetics experiments (e.g. Siever and Woodford, 1979). In a series of experiments Berner and his associates showed how dissolution actually takes place initially at points of crystal defects and then progresses inward apparently uninhibited by any protective coating (Berner and Holdren, 1979; Holdren and Berner 1979; Schott and Berner, 1983; etc.). All of these works are extremely important to understand the aqueous geochemical processes that control the fundamental weathering reaction whereby fresh rock is altered and new minerals and solutions are produced (cf. Tardy, 1971). However, a bridge remains to be built between the aqueous geochemists and the sedimentary petrologists. We need to know the mineralogic compositions of the weathering residues in sand sizes to better estimate the control of climate (rainfall + temperature) on the initial material of a sedimentary cycle.

Unfortunately and surprisingly, no comprehensive work has been done to evaluate quantitatively the effect of relief on sand composition. Textbooks are replete with _ad hoc_ statements which, in general, imply that the rate of mechanical disintegration would be enhanced with increased relief. However, no single study exists which demonstrates that this enhanced mechanical weathering would lead to any difference in the modal compositions of sands in the source region of detrital sediments, if variables other than relief remain constant. One marginally relevent study (Garner, 1959) shows that climate is far more important than relief (up to ~ 6000 m) in controlling clast size in the Andes Mountains. The data of Franzinelli and Potter (1983) from the Amazon basin show that a combination of very low relief, hot humid climate, and ample vegetation can produce sands of quartz arenite composition primarily from granitic bedrocks.

Ruxton (1970) has described some quartz-poor sands from Papua; we have recalculated some of his data to understand the extent of control of relief on sand composition. The bedrocks in Ruxton's area of study comprise pristine and metamorphosed basic and ultrabasic igneous rocks and metagreywackes. The relief is moderate (365m) but the slopes are steep (up to 35^{o}-40^{o}) and frequently exceed the angle of repose. All sand sized material coarser than 0.21 mm consists of rock fragments. Discrete mineral grains show up only in the fine grained fraction (0.075-0.21 mm). The petrographic data from this size fraction show that the material on strongly weathered crests of hills is very different from that on the slopes (Table 3; fig. 3). However, the compositions of the sands that are found on floodplains or on the beaches of Papua are very similar to each other. The beach

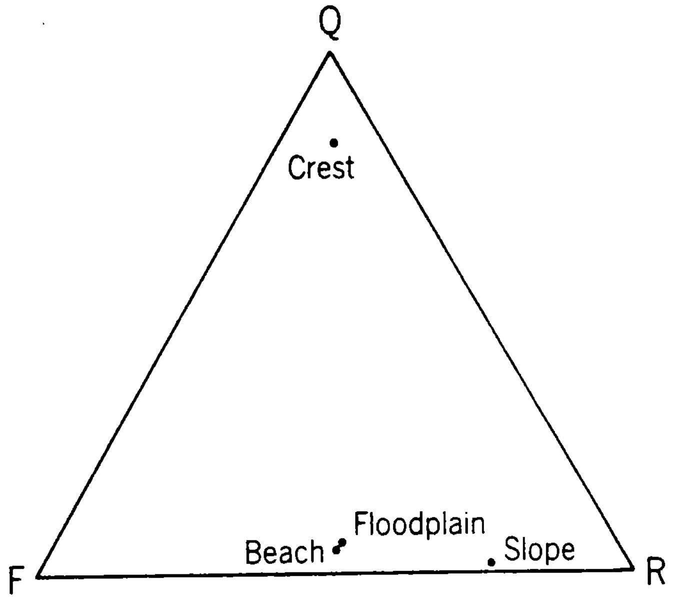

Fig. 3. Recalculated modal data of Holocene sand samples from relatively flat hill crests, steep (up to 35°-40°) hill slopes, and the adjacent floodplains and beaches in Papua (after Ruxton, 1970) are plotted in a standard QFR diagram. Note that the tropical climate has produced a relatively quartz-rich composition in the lateritic soil at hill crests; however, most of the sands, rich in accessory minerals, are compositionally very immature. Hill slope soils must also overwhelmingly contribute to the floodplain and beach sands as seen from the similarity in their compositions. Extreme immaturity of the sands is attributed to the steepness of the hill slopes which must cause a very short residence time of soils, if any, on the slopes.

and floodplain sands are also compositionally much closer to the hillslope sands than they are to the hillcrest regolith. Clearly, the contribution of hillslope material to the basins is much higher than the hilltop material. Note that in Ruxton's study area the slopes are steeper than the angle of repose and the residence time of any soil on these slopes would be extremely low. If there were other studies with similar source rocks on relatively flat lying areas in both arid and humid climates, comparison with Ruxton's data would have been extremely useful. Unfortunately, such is not the case. However, the data in hand do show that slope angle, as a control on the residence time of soil horizons, not relief, indirectly controls the initial composition of the sand sized material released from bedrocks. It appears that low relief might only aid in increasing the residence time of soil thereby increasing the degree of chemical weathering in a source region. Thus, low relief in a humid highland may actually contribute more towards affecting sand composition than high relief in any climate. Although we might suspect that high relief (not to be confused with elevation) is relatively insignificant in controlling detrital mineralogy of sands, we just do not have any quantitative data even to form an opinion. It appears, however, that volumetrically significant

Table 3. Recalculated abundance (in volume percent) of mineralogic components in Holocene sands in the island arc complex in Papua (after Ruxton, 1970). Data on the non-clay fraction pertain to 0.075-0.21 mm size range.

	Hill crest	Hill slope	Floodplain	Beach
Quartz	19	1.5	5	3
Feldspar	2	14	37	31
Rock Fragments	2	46.5	38	32
Accessary Minerals	38	27.5	18	32
Clay	38	10.5	2	2

contribution of sands from hillslopes, if slopes are greater than the angle of repose, could virtually bypass all possible climatic effects documented by the Indiana group. I am convinced that the relative importance of climate, relief, slope angle of hills, and elevation in determining the composition of first cycle sands will form the basis of some extremely significant research in very near future.

SURVIVABILITY OF QUARTZOSE PARTICLES

This introduction to provenance interpretation would remain incomplete if no comment is made on the survivability of detrital particles. I shall not repeat what may be found in standard textbooks on the chemical stabilities of various rock forming minerals under atmospheric conditions (e.g. Garrels and Mackenzie, 1971; Pettijohn et al., 1972; Blatt et al., 1980; Leeder, 1982; etc.). I shall, however, comment on the theoretical aspect of survivability of strained i.e. undulose quartz grains and polycrystalline quartz grains with sutured contacts between subgrains.

Under normal atmospheric conditions and in common soils, quartz does not react with water to form new minerals but does go into solution although the solubility of crystalline silica is very low. Solubility of quartz increases with increasing density of lattice dislocation (Wintsch and Dunning, 1985). Therefore, strained quartz (undulose monocrystalline quartz and polycrystalline quartz grains with sutured contacts between subgrains) is apt to suffer greater degress of dissolution than nonundulose monocrystalline quartz. According to Blatt (1967) this increased solubility makes strained quartz thermodynamically less stable than unstrained quartz grains. Note that any increased dissolution along fractures and cleavage helps the mechanical disintegration of any particle. Blatt's (1967) data do show that the durability of strained and polycrystalline quartz in Holocene sand seem to agree with the above model. However, strain and dislocation of lattices of crystals increase their internal energy and provide greater brittle strength. The phenomenon is that of "work hardening" as referred to in metallurgy. Indeed, Pettijohn et al. (1972) use the term "cold rolling" in describing polycrystalline quartz with sutured contacts of subgrains. At this time, we do not know if increased solubility of strained quartz is more important than the additional brittle strength, in determining the survivability of detrital quartz. This is a problem that needs more careful attention, perhaps with well designed laboratory experiments. It is possible that solubility of quartz grains is important only in soil horizons, whereas the brittle strength of quartz particles continue to be the prime factor in determining the survivability of quartz in fluvial transport (cf. Mack, 1978). Data of Basu (1976) seem to bear out the latter.

CONCLUSIONARY COMMENTS

It should be apparent to the readers that we really have very scanty usable information on the effects of the interactions between climate and relief on compositions of sand released at source areas. Data at hand do show that, if the traditional point counting technique is applied, it is possible to recognize the effects of arid and humid climate in first cycle sediments. However, if hill slopes exceed the angle of repose and the residence time of all slope soil is low, even hot and humid climate would not be as effective to achieve advanced decomposition of bedrocks. Compositions of ancient sandstones believed to have been derived from magmatic arcs (Dickinson and Suczek, 1979; Ingersoll and Suczek, 1981; Yerino and Maynard, 1984; Valloni and Mezzadri, 1984; etc.) are very similar to the modern beach sands of Papua (Ruxton, 1970). Is it possible that the residence times of the regolith/soils in active magmatic arcs have always been very low? Climate has a tremendous influence on the ecology of land organisms. Vascular land plants are notorious for secreting acid at their roots. Some data suggest that the extent and nature of biochemical weathering can be very significant in determining the initial sand composition. Unfortunately, very little follow up work has been done. In short, we sedimentary petrologists have a vast area of potential research open to us.

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