Gamma-ray log shape used as a facies indicator: critical analysis of an oversimplified methodology

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Abstract: Gamma-ray log shapes are often used by geologists to determine sandstone grain size trends and hence depositional facies. However, for the simple methodology of relating shapes to facies to be valid, there must be consistent relationships between gamma-ray log values and clay content and between clay content and grain size. Log to core comparisons and sandstone textural analyses show that these relationships are naturally variable. Consequently, correlation of log shape with grain size trend is tenable only under very limited (and defineable) conditions. A universal application of gamma-ray log shape to grain size trend and depositional facies is wrong.

Three principal gamma-ray log shapes are frequently used as a basis for identifying depositional facies, especially of sandstones. The three are the bell shape (persistently upwards increasing gamma-ray value), the funnel shape (persistently upwards decreasing values) and the cylindrical or blocky shape (stable low values between high shoulders) (Fig. 1). The principal shapes are related to basic depositional sequences which have important sedimentological significance (Fons 1969). The bell shape, for instance, indicates the fining upwards grain size trend typical of a channel sandstone or transgressive marine sand, while the funnel shape indicates the coarsening upwards grain size trend of a barrier bar or delta front deposit (Fig. 1).

The classic syllogism of philosophical logic suggests that two premises can be joined to make a conclusion. It takes the form: 'all S are M, all M are P, therefore all S are P'. The mistakes that can be made in such a formula are part of philosophical folklore.

The use of gamma-ray log shapes to suggest sandstone depositional facies uses just such a syllogism and seems to fall into just such a trap as pleases the philosophers. The formula is: all (S) shaped gamma-ray curves indicate (M) lithological sequences, all (M) lithological sequences indicate (P) depositional facies, therefore all (S) shaped gamma-ray curves indicate (P) depositional facies. For example, all bell-shaped gamma-ray log shapes are indicative of upwards decreasing grain size sequences: all upwards decreasing grain size sequences indicate a channel facies or a transgressive marine facies: therefore, all bell-shaped gamma-ray curves indicate channel facies or transgressive marine facies. Such a stark statement as this clearly creates doubt about a methodology which uses such 'logic'. The philosophical point should not be laboured, but it does show how the methodology can be cut into constituent parts and examined.

The obvious relationship being suggested when gamma-ray log shapes are used in facies analysis, is that gamma-ray changes, besides indicating clay content, mirror grain size-changes. Low log values indicate a coarse grain size while high values indicate fine grain size (Fig. 2). Although this relationship was originally illustrated using the SP (Fons 1969) it was later extended to include the gamma-ray (Serra & Sulpice 1975, Selley 1976). However, the gamma-ray tool does not measure grain size: it measures natural radioactivity. Using the log shapes therefore requires implied relationships. There are three principal ones: (i) the relationship of gamma-ray log response to clay content, (ii) the relationship of clay content to grain size and (iii), the relationship of grain size sequence to depositional facies. The third relationship will not be examined in detail as it is entirely in the realm of sedimentology and will only be considered in the final discussion. The first and second relationships, however, are fundamental to the suggested use of the gamma-ray log shapes and must be examined for proper comment on the methodology (Fig. 2). To do this the gamma-ray log response to clay content and the relationship of clay content to grain size will be considered. To complete the loop, the direct, empirical relationship of the gamma-ray log response to grain size change will be illustrated.

Gamma-ray response and clay content of sandstones (sandstone and clay radioactivity)

The gamma-ray log is a record of a formation's natural radioactivity which comes spon-

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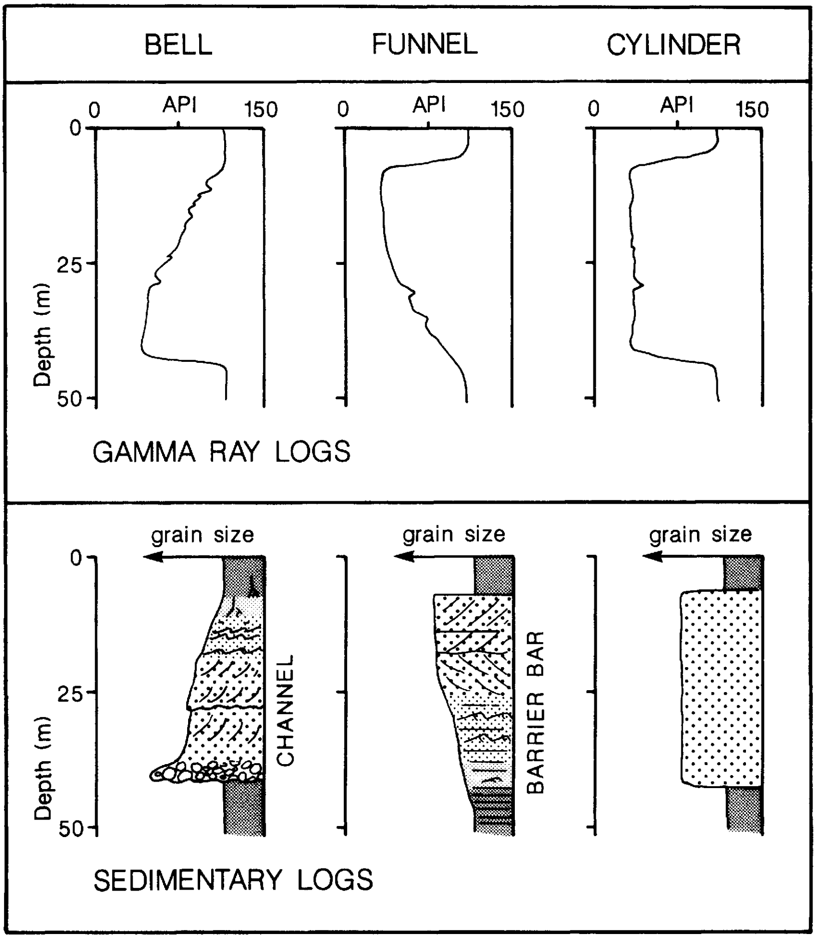

Fig. 1. The three principal gamma-ray log shapes and their corresponding sedimentary interpretation (after Serra & Sulpice 1975).

taneously from naturally occurring uranium (U), thorium (Th) and potassium (K) (Russell 1941). The naturally radioactive elements generally have a far greater concentration in shales than in most other sedimentary rocks. On the contrary, quartz, the principal component of sandstones, does not contain either U, Th or K. Therefore, in sedimentary rocks formed of a mixture of quartz sand and clay, high gamma-ray readings are usually taken to indicate high clay content. Regrettably this is often not the case. All that is radioactive is not necessarily clay and clay is not always radioactive.

Before describing the distribution of radioactivity in sand and clay, it is necessary to define how the word 'clay' is used, there being a certain amount of ambiguity in the term when sediments are described. Here, 'clay' is used in the textural sense, meaning detrital grains with a size of less than 4 μm. However, it is implied that this fraction is essentially made up of clay minerals, as the mineralogical composition controls the natural radioactivity. The use of the word 'clay' will therefore indicate clay sized particles of clay minerals. Any ambiguity created by this dual sense will be clarified in the text where necessary. Shale will be used to indicate lithologies, composed of clay-sized material.

When interpreting gamma-ray log shapes of sandstones, difficulties arise because naturally radioactive silt and sand sized detrital grains are mixed with the non-radioactive quartz grains. In a typical sandstone, quartz will be mixed with feldspars and rock fragments, as well as with clay. Indeed, the usual way of classifying

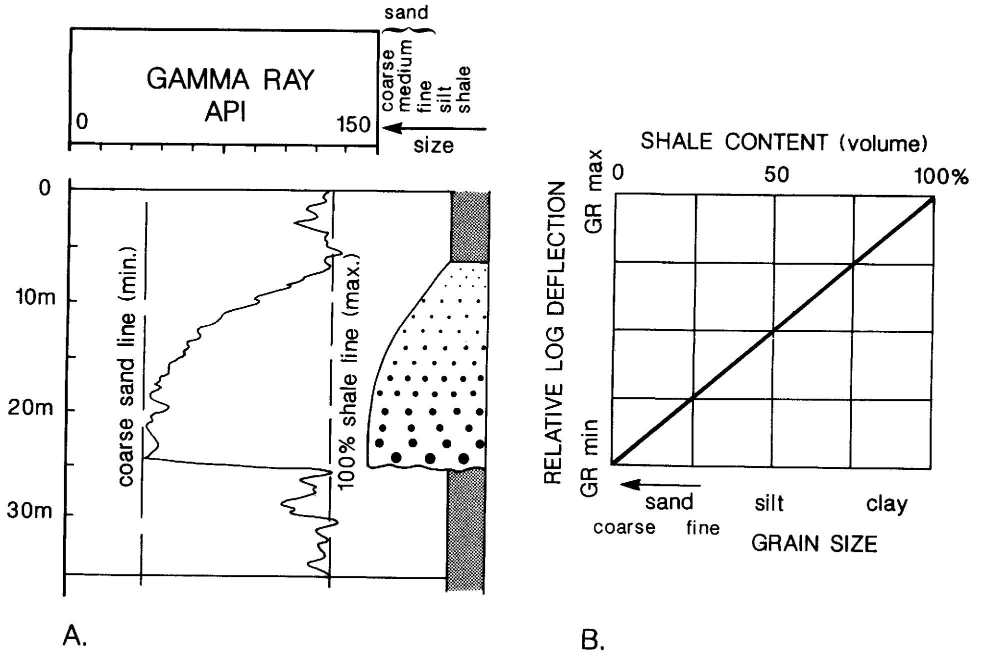

Fig. 2. Schematic representation of the use of the gamma ray log in facies analysis. A. Grain size changes reflected in the gamma ray log. B. Graphical presentation of the semi-quantitative relationships implied (modified from Rider 1986).

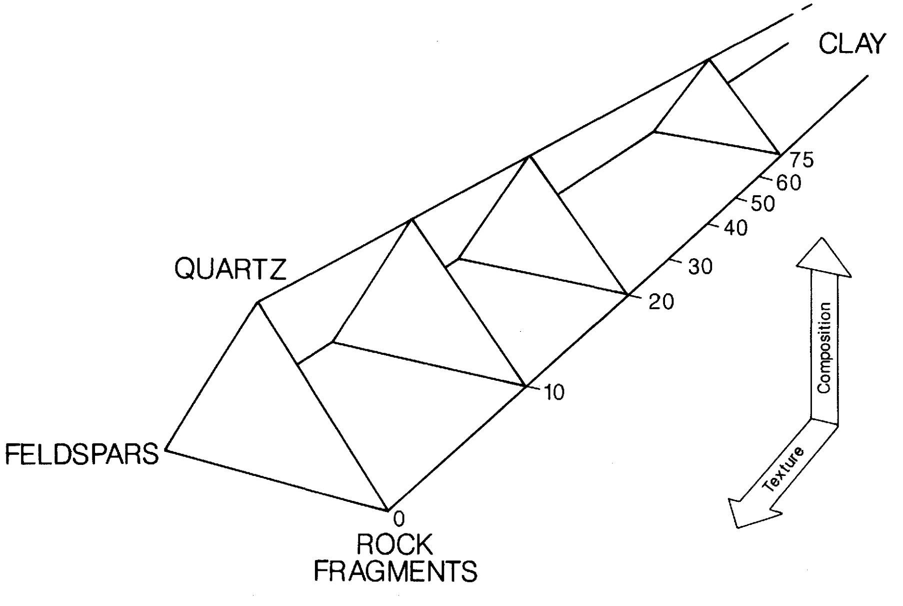

Fig. 3. Diagramatic representation of the elements of sandstone classification, based on both composition and texture (modified from Folk 1954).

sandstones is to express the composition in terms of quartz, feldspar and rock fragments on a triangular graph against detrital clay as a third dimension (Fig. 3). Importantly, this recognises the semi-independent interplay between texture and composition (Folk 1954). The common, naturally radioactive detrital components include potassium feldspars, because of their high potassium content (10–15% in potassic varieties), rock fragments when composed of micas (high potassium content, see Hurst 1990), volcanic clasts (thorium and potassium present but variable) and large clay clasts. Sand sized detrital components cannot therefore be considered as exclusively non-radioactive.

Moreover, clays cannot be considered as exclusively radioactive because clay minerals have a wide range of compositions. In terms of potassium (K), for example, although the average shale contains 2.7% K, the range is from over 8% K in illites to 0% in chlorite. With thorium (Th) and uranium (U) the range is as great (Hurst 1990). The thorium ranges are especially significant since the radioactivity from this source probably contributes about half of the total count (Dypvik & Eriksen 1983). Empirically in terms of total radioactivity, illite will have a much greater contribution than chlorite or kaolinite (Reverdy *et al.* 1983). However, the potassium concentration of illite is normally insignificant in terms of the bulk potassium content of a rock unless concentrations of potassium feldspar and micas are negligible (Cowan & Myers 1988; Hurst 1990). Clearly any change in clay mineral composition will most likely entail a change in radioactivity.

Chemical analyses of some typical sedimentary rocks show well the effects of the natural minerological variations outlined above. An arkose can contain over 5% K_2O while a silty clay contains only just over 3% K_2O (Cox *et al.* 1967). The log example (Fig. 4) illustrates this effect and shows a medium to coarse grained arkosic sandstone without clay but with up to 25% feldspar of which 10% is potassic and therefore radioactive, surrounded by a silty clay composed mainly of kaolinite with a very low natural radioactivity. The result is that the gamma-ray log radioactivity values of the silty clay and the sandstone are very similar. This is a serious complication when using gamma-ray log shapes.

Confusion between clay mineral and detrital mineral radioactivity is complicated even further by the fact that the non-quartz detrital components tend to vary in concentration with grain size just as the clay fraction does (a factor allowed for in the classification of sandstones as

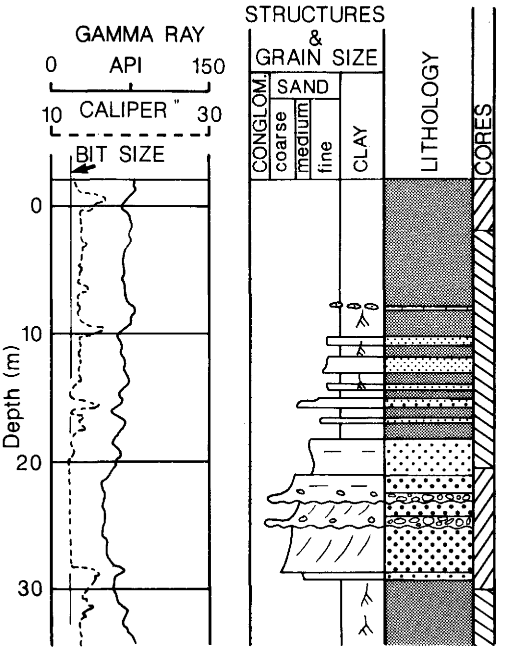

Fig. 4. Arkosic sandstone with an average 25% feldspar content (10% potassic) with a gamma-ray value similar to the surrounding silty shales.

indicated previously, Fig. 3). Overall sandstone composition can, in fact, be expressed as a function of quartz grain size (Davies & Ethridge 1975). Orthoquartzites are generally fine to medium grained, shaly sandstones are fine grained and poly-detrital sands are coarse grained. In terms of natural radioactivity, this means that several regimes are in play against grain size and not just that of clay against quartz. The first example of this effect (Fig. 5) comes from the Middle Jurassic sandstones of the North Sea in which certain grain size classes contain up to 25% of micas (thin section count), naturally radioactive from their high potassium content (6–10%, Hurst 1990). The mica content is seen to vary with grain size changes while the gamma-ray reacts more to a combined function of clay and mica content. A second example shows a dramatic case in which an oil-bearing channel sandstone was considered from a petrophysical examination to have 'shaled out' (in Well 2, Fig. 6). Examination of cores showed that the channel continued but that in this particular well the lower part was dominated by large shale clasts and could be more properly called a shale conglomerate.

These examples clearly illustrate that a high gamma-ray value cannot be equated to high

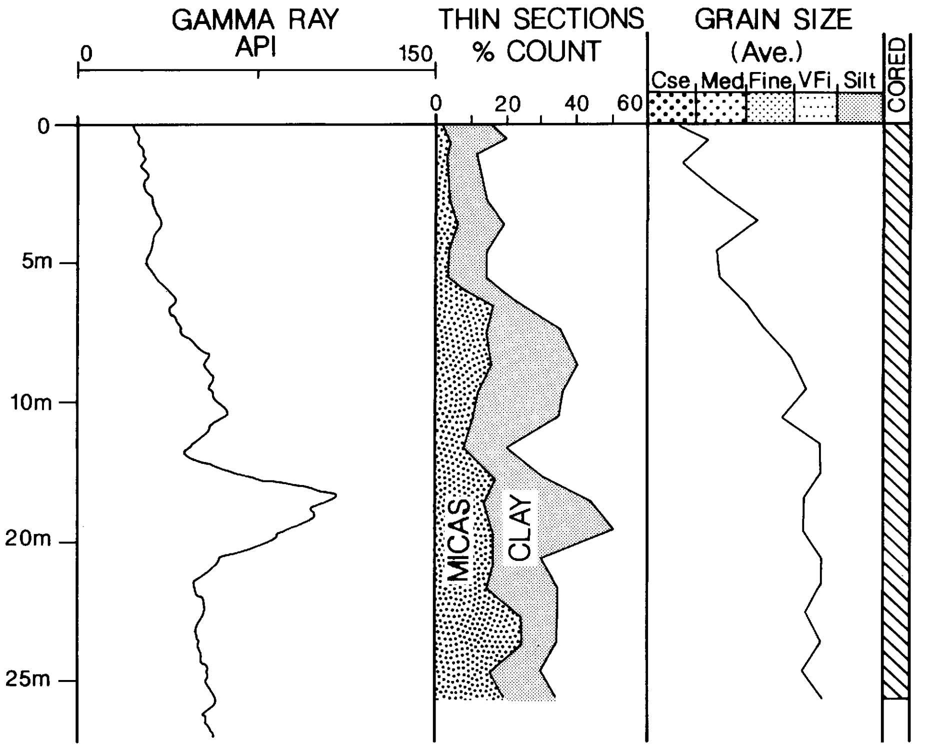

Fig. 5. Gamma-ray log in a sandstone with both radioactive grains (micas) and detrital clays. The micas vary more regularly with overall grain size than the clays.

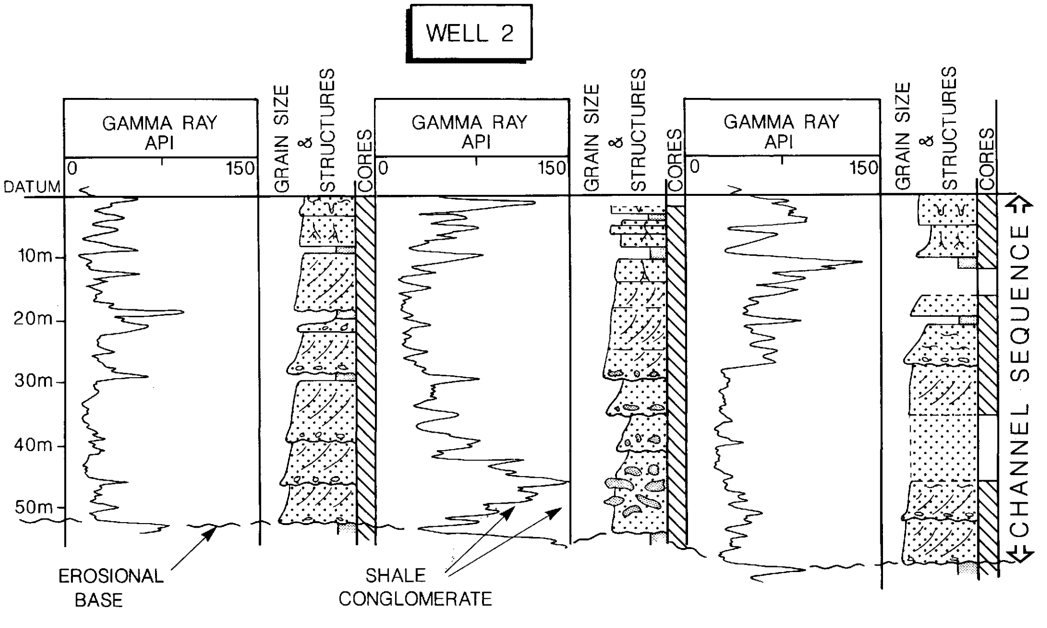

Fig. 6. Channel sandstone sequence across three wells with an interval of high gamma-ray values in Well 2 due to the presence of shale conglomerate.

clay content any more than a low value to a low clay content: the reality is much more complex. The gamma-ray log value of a sandstone is not necessarily related to its clay content.

The clay–grain size relationship

The relationship to be considered next concerns texture, being that between grain size and clay content. There is no doubt that a grain size to clay content correlation exists, but it is by no means the constant relationship required if the proposed log shape analysis methology is to work properly. The following examples illustrate the problems.

Sedimentary petrographers suggest that texture in sandstones can be related to depositional processes and, by inference, depositional environment (Visher 1969). Depositional environment is also believed to affect sandstone composition within, of course, the limits imposed by the grain size and mineralogical content of the sediment source. Some authors go so far as to claim that a depositional environment can be identified from composition (Davies & Ethridge 1975). Although sandstone texture and composition are identifiable as separate attributes, they are very closely related albeit in a variable manner. For example, a textural analysis of some German sandstones shows that clay content varies consistently with grain size in alluvial (Molasse) sandstones, but that in a well winnowed marine sandstone (Dogger) no such relationship is seen (Fig. 7). It appears that in rapidly deposited sands such as occur in the Molasse, the amount of clay is associated with the dominant grain size, but in environments where there is long duration winnowing, all clay is absent regardless of grain size: the clay content is no longer related to sand size fractions. These are just two cases.

Much modern work on primary textures and structures in sandstones aims to analyse the behaviour of various grain size classes under different hydraulic conditions. The mode of transport, of deposition or of erosion, is cross-linked to current velocity and expressed in the resulting deposit as a range in grain size (Allen 1985). The empirical differences in the relationship between clay content and grain size shown in the German sandstone examples (Fig. 7) have a theoretical basis. The variation is natural rather than exceptional and related to the dominant hydraulic processes in particular environments. Deposition from a turbidity current will create a different relationship between clay content and grain size to that created by marine

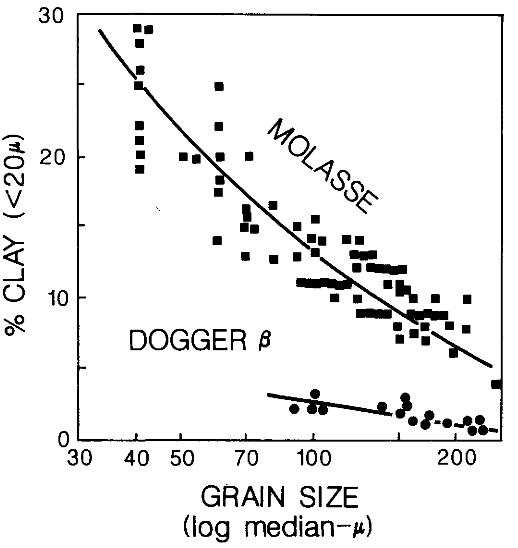

Fig. 7. The relationship between grain size and clay content in two German sandstones, the alluvial Molasse and the marine Dogger (from Pettijohn *et al.* 1972)

winnowing or by deposition in a river current. Without attempting to resolve the intricacy of these inter-relationships, it is clear that clay to grain size correlations are as varied as are hydraulic conditions.

An additional complication which affects these observations on primary relationships is the frequent occurrence of clay mineral diagenesis in sandstones (e.g. Almon *et al.* 1976). Diagenesis may involve both clay mineral neoformation or destruction. Both change the clay to grain size relationships and, consequently, the relationship between the location of natural radioactivity in specific minerals and in grain size classes. (For example, dissolution of detrital potassium feldspar and neoformation of illite will change the location of potassium in minerals and thereby increase the radioactivity present in the clay-sized fraction.) Although certain diagenetic processes may be facies and grain size controlled (e.g. Hawkins 1978), the secondary changes can only make the primary clay to grain size relationships more complex and unpredictable. An added element of uncertainty in the understanding of gamma-ray log shapes.

Empirical gamma-ray log to grain size relationships

To put the preceeding somewhat theoretical aspects into context, it is necessary to examine empirical comparisons between cores and gamma-ray logs.

That there can be a close relationship between grain size and gamma-ray log values, is illustrated using core derived measurements (Fig. 8). A slightly different method of comparing core and log data shows a similar close relationship (Fig. 9A). Both these examples are from deltaic environments. Once a good gamma-ray log to grain size relationship has been demonstrated, it is a natural tendency to add a sedimentological dimension and an interpretation of depositional environment. Indeed, the most often quoted example of gamma-ray log shape is a fining upwards sequence from a fluvial channel or point bar with a classic bell-shaped gamma-ray log (Fig. 10). These convincing and valid examples can create a tendency to believe that a simple relationship between the gamma-ray log and sediment grain size is always present. Of course it is not.

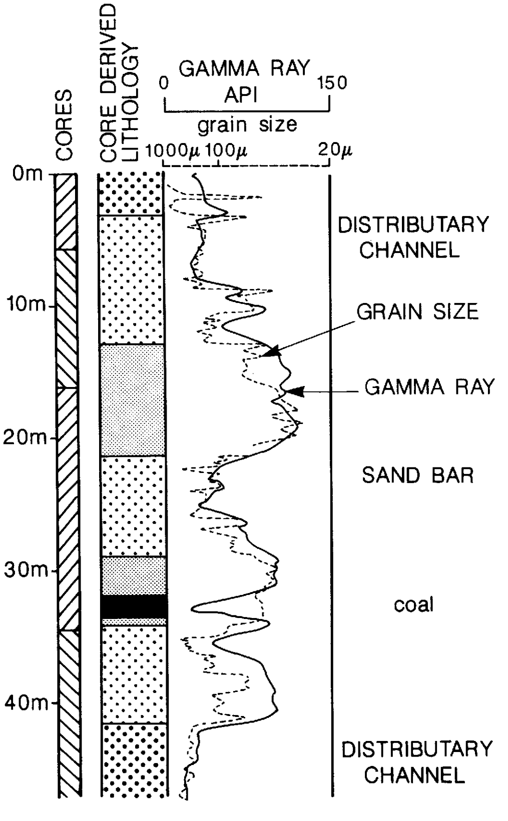

Fig. 8. Very close relationship between gamma-ray log values and core-measured sandstone grain size from a deltaic environment (from Simon-Brygoo 1980).

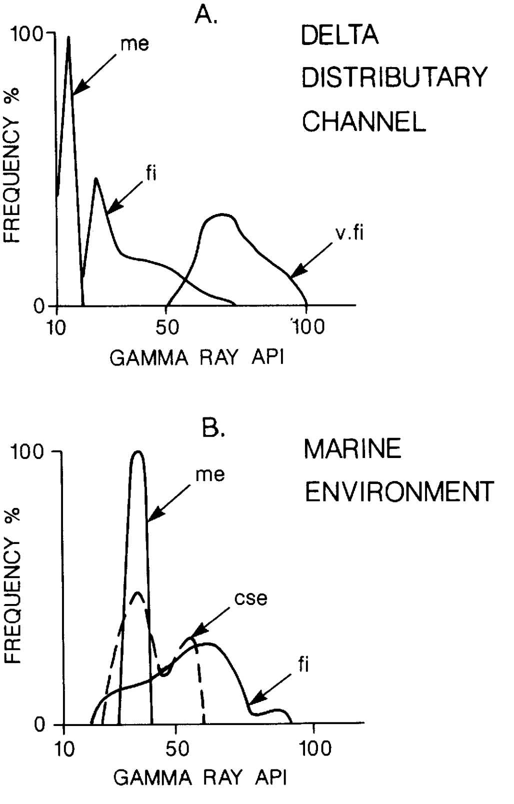

Fig. 9. Gamma-ray log values compared to sandstone grain size classes. A: Alluvial delta distributary sandstone. B: Winnowed marine sandstone. (from Simon-Brygoo 1980).

A sandstone deposited by turbidity currents (Fig. 11) illustrates that there is very little relationship between the texture seen in cores and the gamma-ray response. Log shapes give absolutely no indication of grain size changes. In this example, there appears to be a persistent clay-sized fraction regardless of the coarse grained fraction, be it sandstone or conglomerate. A similar lack of correlation is shown by a fluvial, fining upwards sequence identified from core (Fig. 12). It is not associated with the expected bell shape on the gamma-ray log but with a subdued funnel shape. Finally, in the general type of presentation, grain size classes are seen to have no relationship to gamma-ray values for the identified marine environment (Fig. 9B). These examples, in fact, represent the normal case rather than the unusual.

An aspect which adds complexity to the empirical comparisons is diagenesis. The effect is seen not just in the clay minerals, as has already been touched upon, but also in the detrital

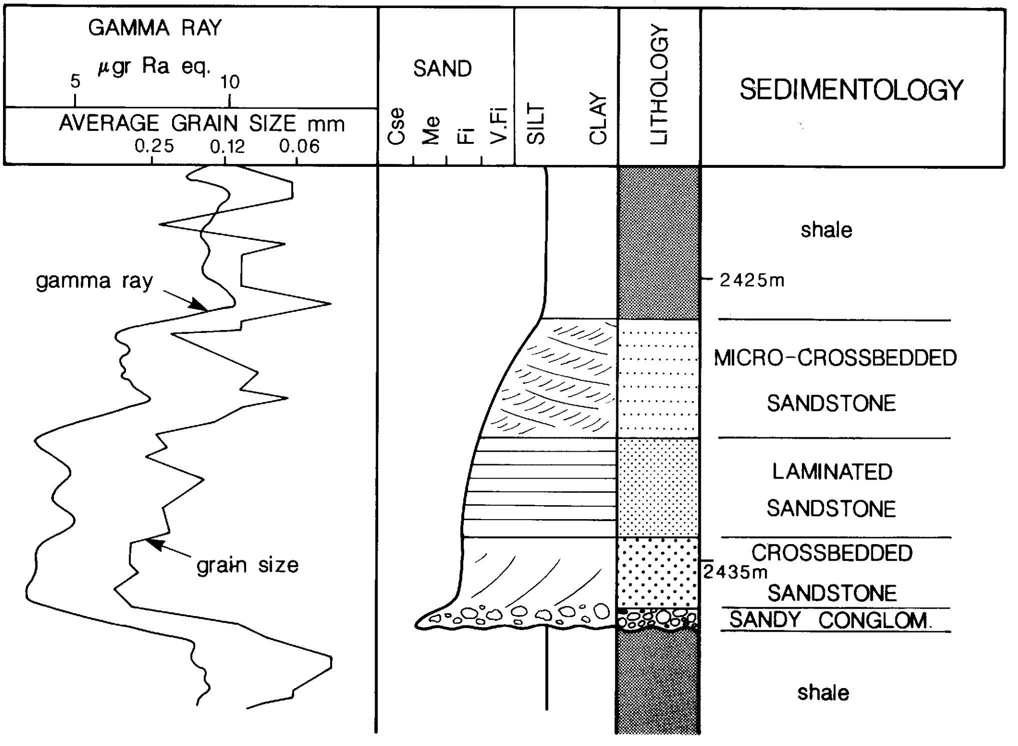

Fig. 10. Typical bell shaped gamma-ray log corresponding to a fluvial, fining upward point bar sandstone sequence (from Serra & Sulpice 1975).

minerals themselves, such as feldspars, which are chemically unstable in many sub-surface conditions. The effect that diagenetic changes have on radioactivity is very difficult to assess. For example on the shelf off mid-Norway, the depth-temperature controlled diagenetic change from kaolinite to illite requires an addition of potassium, the source for which may be pore water potassium derived from feldspar destruction (Bjørlykke *et al.* 1986). Formation of illite presumably concentrates potassium in the clay-size fraction of the rock at the expense of potassium feldspar present in the sand fraction. However, diagenetic clay minerals may be less radioactive than the detrital ones (A. Hurst, pers. comm.) so the overall effect on the gamma-ray log is difficult to evaluate. Diagenesis commonly causes changes in the distribution of the natural radioactivity in minerals, almost certainly confusing any simple relationship between grain size and gamma-ray log value.

Discussion

As the above examples show, there is a dilemma: sometimes the gamma-ray log shapes faithfully correlate with grain size variations, sometimes they do not.

As was stated at the outset, for the gamma-ray response to correlate with grain size variations two conditions must be met: the gamma ray must correlate with clay content, and the clay content must correlate with grain size. An inversion of this proposition is now more appropriate: when the gamma-ray log does correlate with grain size variations, then all the conditions necessary for the relationship to hold are met. These are that only an admixture of radioactive clay and non-radioactive quartz are involved and that the mode of deposition creates a close relationship between the grain size and the amount of dispersed clay. Empirically, it seems that it is especially in fluvio-deltaic environments (Figs 8 & 10) where these conditions are met (e.g. Flint *et al.* 1988). Moreover, in these cases it is not just the gamma-ray log shape which may be used; it is any variation in value, so that if core material is available, the grain size classes may be correlated in gross terms to actual gamma-ray log readings (Fig. 9A). But this does not create a general rule.

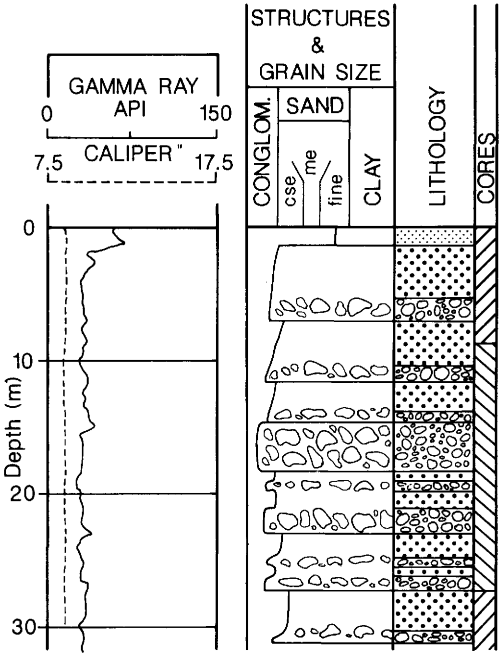

Fig. 11. Lack of correlation between gamma-ray log response and grain size variation in a very coarse grained sequence deposited by turbidity currents.

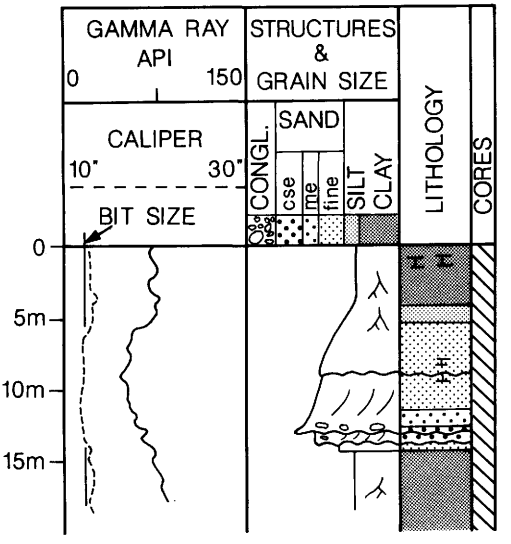

Fig. 12. Fining-upwards fluvial sequence with no bell shaped gamma-ray log.

There are two principal reasons for complications. Firstly, as has been illustrated (Figs 3–7), the ideal relationship between grain size and gamma-ray log response is disturbed by two primary factors, one compositional, the other textural. In terms of composition, it has been shown that it is quite normal in a sandstone for there to be non-clay detrital minerals which have a natural radioactivity. Their abundance is frequently related to grain size but it is quite independent of the clay fraction. A change in gamma-ray value simply indicates a change in the naturally radioactive detrital grains and not a grain size change with a concomitant variation in clay content. Secondly, the variation of the clay content has been shown not to always follow the grain size variation. Indeed the relationship is probably, in some way, related to the environment of deposition and is hence highly variable. Even when there are no naturally radioactive detrital grains present, gamma-ray variations do not reliably indicate grain size variations. This is the effect of texture. Added to this are the present but undefineable effects of diagenesis. Consequently, compositional, textural and diagenetic variability all cause the relationship between gamma-ray log shape or log value and grain size to break down.

It is quite clear that universal rules and a universal use of the gamma-ray log as an indicator of sandstone grain size variation is wrong. It may be correct in selected cases but this can only be confirmed after calibration with core material. The application benefits from an understanding of the principles involved.

This does not mean that there is no place for logs in the interpretation of depositional environments. Quite the contrary, it points to ways in which logs may be used. The gamma-ray log on its own has severe limitations. Furthermore, why should it be used on its own — because it is apparently simple? The spectral gamma-ray log could be used to refine the interpretation of the radioactivity of the simple gamma ray but most of the problems outlined above would still not be avoided. Also, why should only the coarse-grained intervals be analysed. In logging, unlike at outcrop, shales and silts are eminently 'visible'. Indeed, it is frequently the fine-grained intervals that have the most distinctive log signatures. The rule, therefore, is that analysing logs for facies information should include the whole log suite, not just the gamma-ray log, and the whole sediment sequence, reservoir and non-reservoir.

The final example illustrates this point (Fig. 13). It concerns a small fining-upward sequence surrounded by over-bank silty shales containing calcretes, and an upper, more complex, possibly

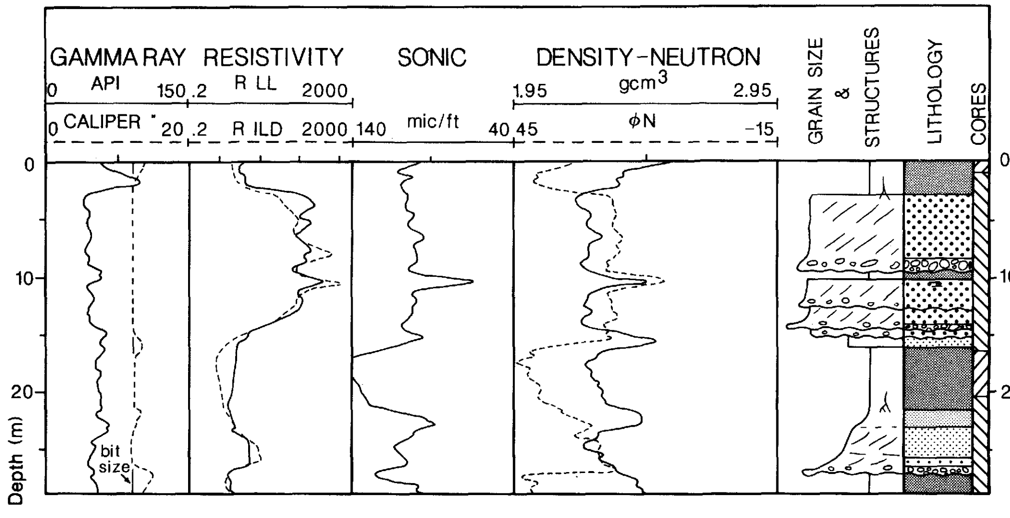

Fig. 13. Two sand bodies with a full set of corresponding logs. Lithological and textural information can be interpreted from each, especially the neutron density.

braided sand body. The shales are kaolinitic and have a low natural radioactivity. Conversely, the sands have a relatively high natural radioactivity because of abundant potassium feldspar, which has not been altered by diagenesis. The result is that the gamma-ray log is rather featureless and differentiates poorly between sand and shale. The neutron log, on the contrary, reacts to free and bound water content, thus allowing clear identification of the clay layers. The compact calcrete layers are seen on the density log but especially on the sonic log which is sensitive to horizontally continuous features. In the sandstone intervals the density log shows porosity variations which are related to textural changes. These are further linked in part to grain size variations and in part to diagenesis. The resistivity logs indicate textural changes in the sandstones in terms of differences in fluid displacements around the borehole. Each log, properly interpreted within its limitations, adds an element to the lithological, textural and eventually sedimentological description. The logs should lead us to a textural and compositional description, not a final interpretation of environment of deposition. Many other data are involved in that. In conclusion, therefore, ringing the virtues of a bell-shaped gamma-ray log is doing the science of geological log interpretation a gross disservice.

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