Equation of estimation of sedimentation rates: Applications to sequence stratigraphy

M. Aslam
Department of Geology, Aligarh Muslim University, Aligarh 202 002, India

Using existing sea-level curves, the equation (Δ Sub + ΔE − Δ Sed = ΔD) shows that transgressive–regressive sequences cannot result solely from eustatic variation. The space created by subsidence is greater than that provided by eustatic rise. However, eustatic variation could have triggered sequence development if superimposed on a basin with relatively constant values of the other parameters. The equation put some well-known geological principles on a simple quantitative basis. It encourages precision in definition of variables, and may lead to further development of quantitative techniques in stratigraphy and sedimentology.

PETER Vail and his colleagues[1] at Exxon have brought about a revolution in stratigraphic thinking in the past fifteen years. This communication presents some well-known geological concepts like transgression–regression in the form of simple mathematical equations.

Stratigraphers and sedimentologists have known that the variables controlling transgressions and regressions in sedimentary sequences are subsidence, eustatic sea-level change, and the amount of sedimentation[2]. These are the variables in the equation of sedimentation developed here.

The subsidence or uplift of the substratum is the change in height of a surface on which the sediment was deposited. The type of subsidence is not relevant to the equation – it can be tectonic (thermal cooling of a passive margin or lithospheric response to thrust loading), the result of sediment or water loading, or compaction of older sediments. The variable Δ Sub is the sum of all the types of subsidence described above. Where uplift is taking place, the variable has negative value.

The vertical change in absolute sea-level during a period of deposition is of interest because of the interpretation by Vail, Mitchum and Thompson[1] of unconformity-bounded seismic sequences. The compilation of post-Triassic sea-level data by Haq, Hardenbol and Vail[3] shows two temporal scales of variation-long term (> tens of millions of years) of 200–300 m amplitude, and shorter term (< 3 million years) of 50–150 m.

The depth of water is the parameter which is most reflected by the sediments – the facies, and transgressions and regressions. The change in water depth over the sediment surface can be evaluated in some circumstances, i.e. near sea-level, but in other cases, such as in abyssal or bathyal conditions, the absolute error is much greater.

The net thickness of sediment deposited at a location may be positive or negative. The thickness is controlled by two different factors: (i) limitation of the space available to be filled by sediment (accommodation space); and (ii) variations in the amount of sediment supplied when the space is sufficient to accommodate it. Obviously the thicknesses can be converted to sedimentation rates by dividing the period of deposition. The rate of sediment input can vary for several reasons, the most basic of which is changes in erosion rates in the source areas because of changes in topographic relief. Rates may also vary because of climatic fluctuations generated by effects such as Milankovitch cycles. On a much shorter scale, rates may vary because of autocyclic processes, factors intrinsic to the sedimentary environment. This can best be seen in deltaic environment, where lobes prograde for 1000–2000 years and subsequent shifting of a distributary away from the area results in a low rate of sediment supply and because of subsidence, eventually a transgression[4].

Variations in the parameters Δ Sed and ΔD describe some aspects of the stratigraphy and sedimentology of the deposit. If ΔD is positive, a transgression results and if negative, a regression. A positive Δ Sed implies net deposition which means an onlapping sequence because all sedimentary deposits must onlap their substrate in places. A negative Δ Sed is represented by an unconformity. Formation of an unconformity (negative or zero Δ Sed) implies that the sediment surface was above sea-level, either because of eustatic fall (negative ΔE) or tectonic uplift (negative Δ Sub), or a combination of both. Different combination of these variables are illustrated in Figure 1.

Figure 2 shows the relationships among the parameters in one place at Time 1 and Time 2. The net sedimentation (Δ Sed) equals S_2 minus S_1, and change in depth (ΔD) equals D_2 minus D_1. It is obvious from the above figure,

$$\Delta\,\mathrm{Sub} + S_1 + D_1 + \Delta E = S_2 + D_2\,,$$

$$\text{i.e. } \Delta\,\mathrm{Sub} + \Delta E - (S_2 - S_1) = (D_2 - D_1)\,,$$

$$\text{i.e. } \Delta\,\mathrm{Sub} + \Delta E - \Delta\,\mathrm{Sed} = \Delta D\,. \qquad (1)$$

Thus, the relative sea-level change (Δ Sub + ΔE) minus the thickness of sediment deposited in time intervals 2 and 1 equals the change in depth of the basin. By differentiating with respect to time, the equation can be written in terms of rates:

$$\mathrm{d\,Sub}/\mathrm{d}t + \mathrm{d}E/\mathrm{d}t - \mathrm{d\,Sed}/\mathrm{d}t = \mathrm{d}D/\mathrm{d}t\,.$$

This simple equation serves to put into a mathematical relationship the variables which are important in controlling the stratigraphy and sedimentology of the near shore deposit.

The equation applies to any arbitrary unit of sediment, but has more significant implications for interpretations of sequences defined on a sedimentologic or stratigraphic basis. A transgressive–regressive sequence is an individual depositional sequence in which the shoreline moves back and forth, and water depth at a location

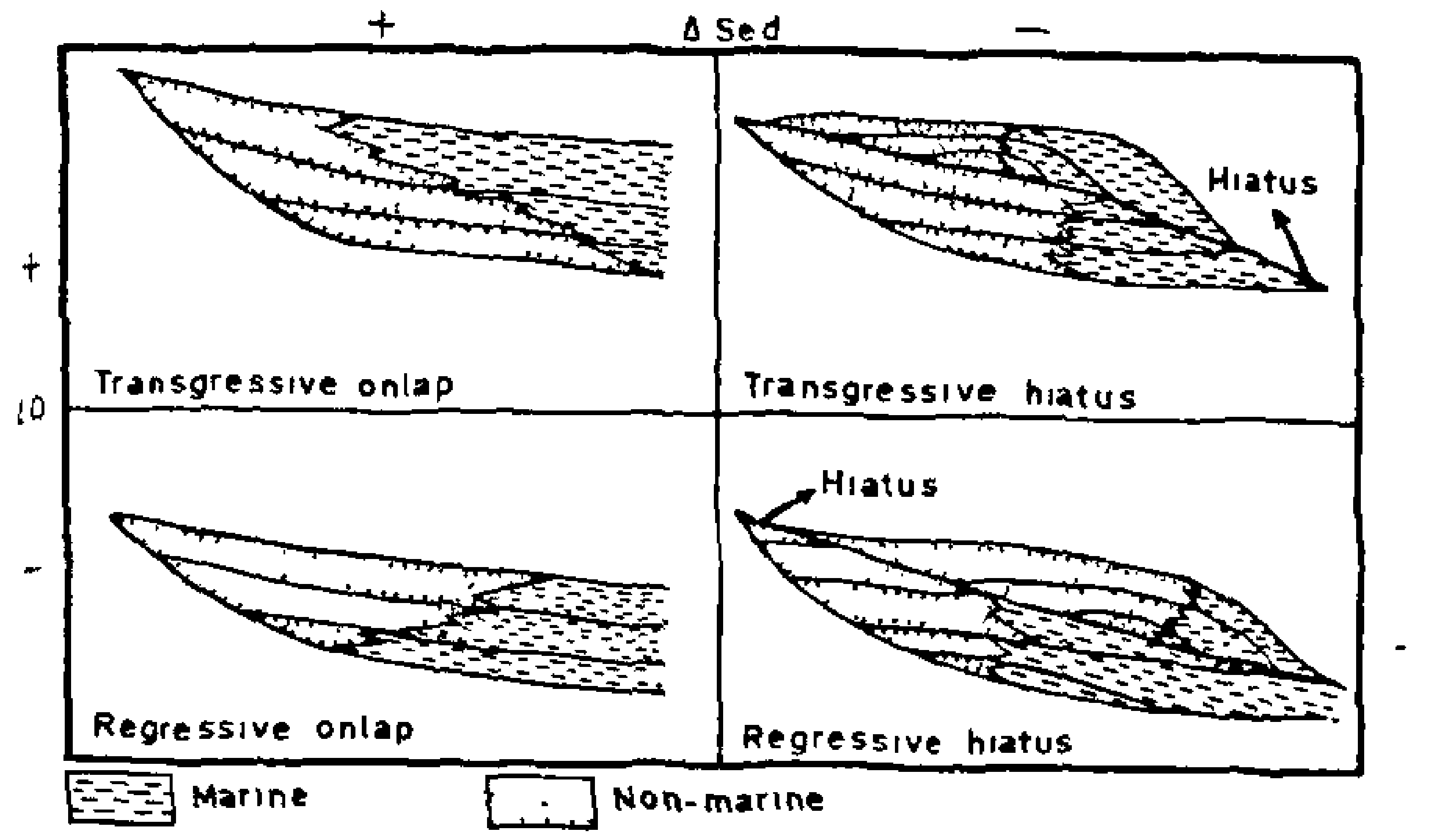

Figure 1. Diagram illustrating differences in sequences with variations in sedimentation (Δ Sed), and change in depth (Δ D). For negative values of Δ Sed, a hiatus or unconformity (Type 1 of van Wagoner *et al*[9]) is created. The relationships of facies immediately above and below the hiatuses are drawn to illustrate the value of Δ D

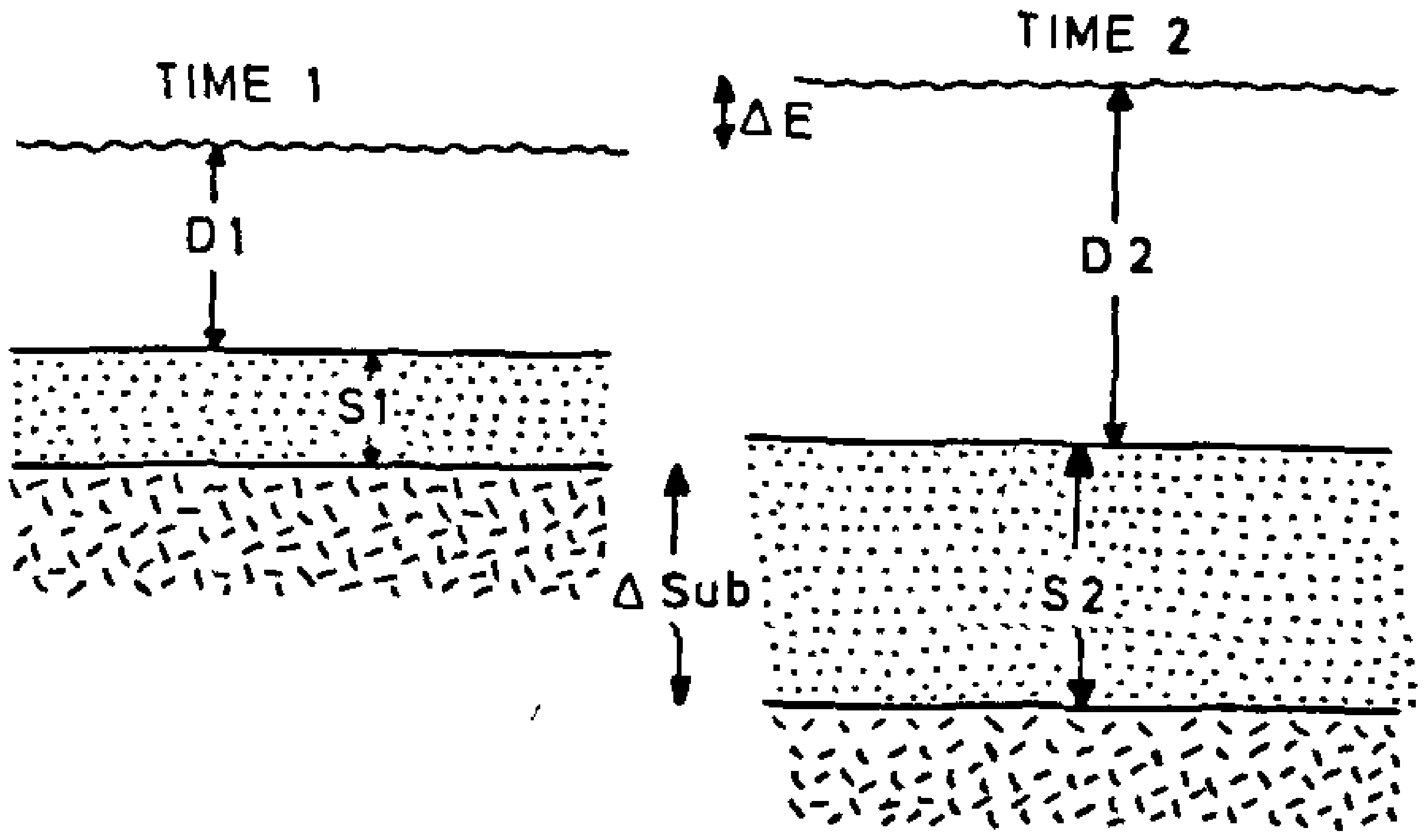

Figure 2. A diagram showing conditions at any point at Time 1 and Time 2. The substratum is dashed and the sediment is stippled.

also increases and decreases.

The implication of equation (1) is that a change in any variable can be due to variation in any combination of the others and that at any single location, there is no absolutely sure way of sorting out the cause of any change. Burton *et al.*[5] discuss the problems of estimating eustatic variation from the stratigraphic record and come to the same conclusion. The transgression–regression, and development of unconformity-bounded sedimentary sequences can reflect any combination of ΔSub, ΔE, and ΔSed, and no single cause can be proved. When a transgression occurs, $\Delta D > 0$, therefore from equation (1)

$$\Delta \text{Sub} + \Delta E > \Delta \text{Sed}.$$

The relative sea-level rise ($\Delta \text{Sub} + \Delta E$) is greater than the thickness of sediment deposited. From one shoreline to the shoreline in the next sequence, $\Delta D = 0$, since by definition each is at sea-level. The thickness of sediment deposited equals the relative rise in sea-level.

The Early Albin Spirit River Formation of Alberta, Canada is a 300 m thick coarsening-upward sequence composed of eight transgressive–regressive parasequences[6]. The stratigraphic data[7] combined with the DNAG Cretaceous time scale allow an estimate of the time-span of deposition of about 3 Myr. If the time for each transgressive–regressive sequence is assumed to be the same, it is 0.375 Myr. To test the interpretation of eustatic control, the assumption is made that each individual sequence is generated only by eustatic sea-level rise ($\Delta \text{Sub} = 0$). From a shoreline to the succeeding one, $\Delta D = 0$, therefore from equation (1), $\Delta E = \Delta \text{Sed}$. The sequences are 30–50 m thick, so the rate of sea-level rise is 30–50 m in 0.375 Myr or 80–130 m Myr^{-1}. Published sea-level curves[3, 8] allow estimation of an Early Albian sea-level rise in the range of 10–30 m Myr^{-1}. Decompaction of the sediments would increase the space required for each sequence, and hence also increase the difference still further. The discrepancy between the two estimates of the rate of sea-level rise implies that the individual transgressive–regressive sequences in the Spirit River Formation cannot be reasonably attributed only to eustatic sea-level rise. This conclusion agrees with that of Vail *et al.*[1] who concluded that parasequences are not directly controlled by eustacy and cannot be correlated over wide areas. Shorter period fluctuations could be invoked to account for the difference in rates. This can be partly overcome by considering the entire Spirit River Formation ~ 300 m thick, deposited in about 3 Myr. The rate of sea-level rise by the same method is about 100 Myr^{-1}. If the rate of rise from the published curves is correct (about 20 m Myr^{-1}), then about 60 m of the accommodation space for Spirit River Formation could have been created by eustatic sea-level rise. The rates of sedimentation and subsidence in this basin were higher on average than rates of eustatic rise in the Early Albian.

Thus, the equation does imply, however, that minor eustatic sea-level fluctuations added to uniform and continuous subsidence and sediment supply, could trigger variations in depth, i.e. transgressions and regressions.

---

1. Vail, P. R, Mitchum, R. M Jr. and Thompson, S., *Mem. Am. Assoc. Petrol. Geol.*, 1977, **26**, 83–98.
2. Curray, J. R, in *Papers in Marine Geology* (ed. Miller, R. L.), Macmillan, New York, 1964, pp. 175–203.
3. Haq, B. U, Hardenbol, J and Vail, P. R, *Science*, 1987, **235**, 1156–1157
4. Frazier, D E, *Trans Gulf Cst. Assoc. Geol Soc*, 1967, **17**, 287–315
5. Burton, R, Kendall, C. G. St C. and Lerch, I, *Earth Sci. Rev*, 1987, **24**, 237–277.
6. Cant, D. J., *J. Sediment. Petrol.*, 1984, **54**, 541–556.
7. Stott, D. F., *Bull. Geol Surv. Canada*, 1982, **328**, 124.
8. Watts, A. B and Thorne, J., *Mar. Petrol. Geol.*, 1984, **1**, 319–339.
9. van Wagoner, J. C, Mitchum, R. M. Jr., Posamentier, H W. and Vail, P. R., *Am. Assoc. Petrol. Geol Studies in Geology*, 1987, **27**, 11–14.

ACKNOWLEDGEMENTS This paper has benefited from review, discussion and formulation of the nonlinear equation by Dr Mursaleen, Department of Mathematics and Irfan A. Khan, B E, Student (F), Z. H E College, AMU, Aligarh. Financial support for this research was provided by the CSIR, New Delhi

Received 11 November 1993, revised accepted 27 June 1994