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Sizes of submarine slides and their significance

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Abstract—A striking discrepancy is shown between the sizes of submarine slide or slump sheets recognised from seismic profiling on present continental margins and the sizes of possibly analogous sheets described from the ancient on-land record. The recent slides are, on average, several orders of magnitude larger in cross-sectional area than their supposed ancient equivalents. Where then are the true ancient analogues of these large recent slide sheets? Are they genuinely absent in the geological record or have they not been recognised? A list is given of characteristics of large continental margin slides which could be recognised in the on-land record. These include their size and the extent to which they are allochthonous, their dominant content of continental margin sediments, their high-level, non-metamorphic deformation and, most critically, their superposition of shallower over deeper water sediments. Using these criteria on typical ancient allochthonous sediment masses shows that most could not have been down-margin slides; only two convincing pre-Pleistocene examples have been found. Therefore the problem remains of whether more examples could exist or whether post-glacial conditions make present margins unique.

INTRODUCTION

This paper makes the simple observation that the submarine slides now commonly revealed by seismic reflection profiling on present-day continental margins are, on average, several orders of magnitude larger than the slumps and slides inferred from the on-land ancient geological record. On one level this is merely a semantic curiosity reflecting two differing scales of geological observation. However, the size contrast raises several more important questions. One in particular will be posed but not solved; where are the analogues of the larger continental margin slides in the ancient record?

No attempt will be made here to review characteristics of submarine slides other than their size. Features of slides on present continental margins have been reviewed by Moore (1977) and Embley & Jacobi (1977). The essential feature of all such slides is the geometrical evidence from seismic profiles that bodies of sediment have moved downslope *en masse*. This is also the process envisaged for slides or slumps described from the ancient geological record. No review of ancient slides is available, although Helwig (1970) and Woodcock (1976b) assess criteria for distinguishing ancient slumps and slides from other deformation phenomena. Other recent papers citing the main literature on ancient slumps and slides are those of Corbett (1973), Rupke (1976), Stone (1976) and Woodcock (1976a, 1979).

SLIDES AND SLUMPS: SEMANTICS

Discussion of slides and slumps is clouded by the variable and imprecise use of these terms in the geological literature. They are used by three groups of earth scientists; engineering geologists, sedimentary/structural geologists and marine geophysicists. In the early part of this century, when the third group did not exist, the terms slump, slide, glide and slip were all used in an ill-defined way for a range of down-slope rock or sediment movements. Sharpe (1938) proposed that slump be applied only to "downward slipping of a mass of rock or unconsolidated material of any size, moving as a unit or as several subsidiary units, usually with backward rotation on a more or less horizontal axis parallel to the slope from which it descends". Subsequent engineering geology usage has adhered closely to this definition, especially with respect to the rotational motion on a concave upwards shear plane (Coates 1977). In this usage a slump is only one of several types of slide, where slide includes all downslope mass movements "with displacement along recognised shear surfaces where the ruptured mass moves with some semblance of unitary motion" (Coates 1977). A slide is distinct from a flow, where displacements are distributed continuously through the mass.

In contrast with the applied practice, sedimentologists and structural geologists have continued to use the terms slump and slide interchangeably, perhaps following the lead of Jones (1938, 1940). At present the term slump is by far the more common, and is usually used with no implication of rotational movement. Marine geophysicists have inherited this same imprecise usage previously established for submarine movements by Daly (1936) and Stetson & Smith (1938). Again, slump has become the more common, although there is now a move to apply the precise terminology (Moore 1977).

Because a more standardized terminology seems desirable, slump and slide will be used in their original precise sense throughout this paper. Therefore, the term slide may refer to both rotational and non-rotational slope failures and may often refer to structures described as slumps in the source literature.

SLIDE SHEET SIZES

The sizes of a large sample of submarine slides are plotted on Fig. 1. Slides are divided into those seen on

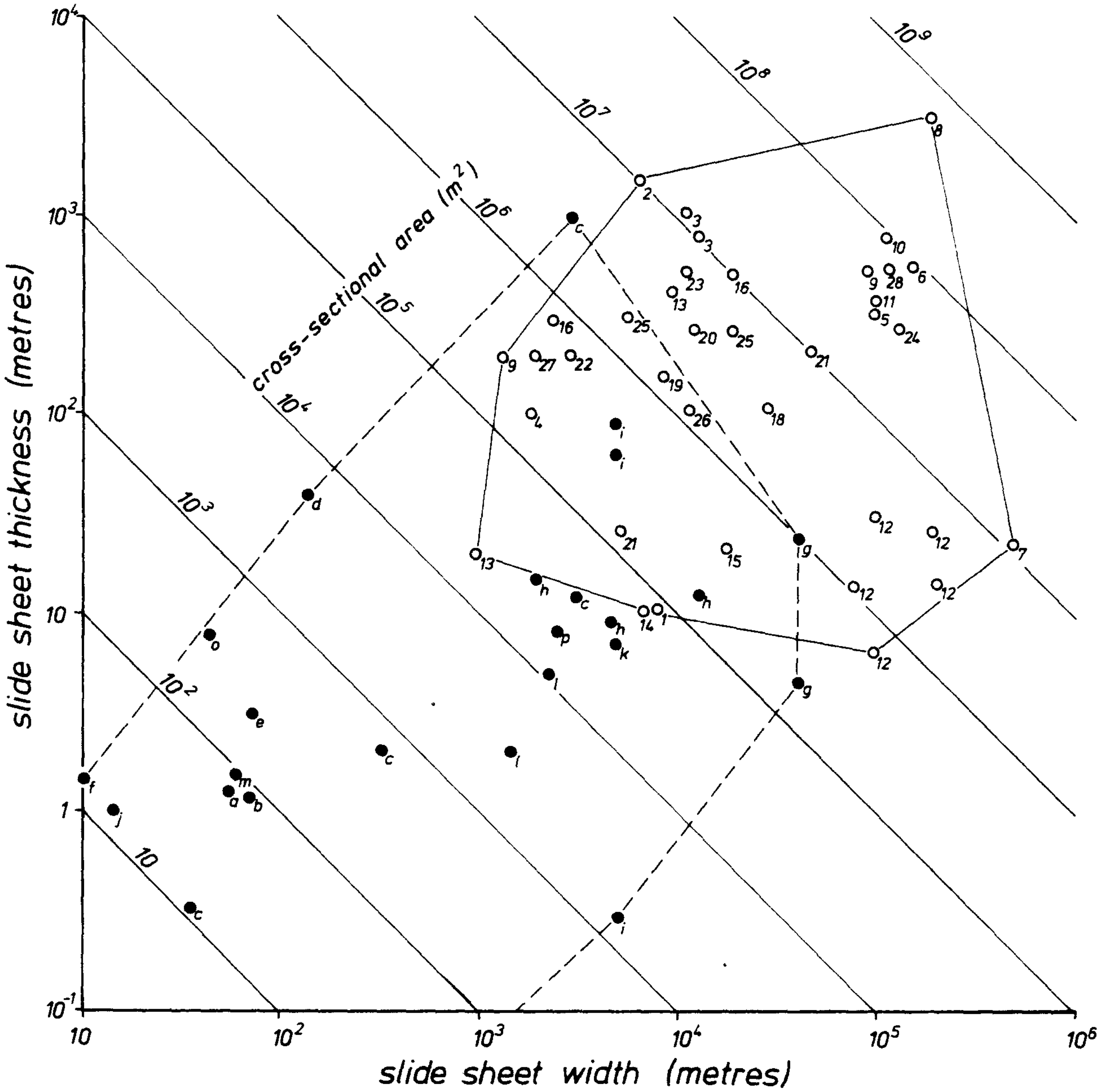

Fig. 1. Plot of average thickness against average width of slide sheets from present continental margins (open circles) and from ancient on-land sequences (solid circles). Data are from following sources: 1. Bartolini *et al.* 1972, 2. Biju Duval *et al.* 1974, 3. Coulbourn & Moberly 1977, 4. Coulter & Migliaccio 1966, 5. Dingle 1977, 6. DSDP 1977, 7. Embley 1976, 8. Emery *et al.* 1970, 9. Emery & Uchupi 1972, 10. Emery *et al.* 1965, 11. Heezen & Drake 1964, 12. Jacobi 1976, 13. Kelling & Stanley 1970, 14. Lewis 1971, 15. Molnia *et al.* 1977, 16. Moore *et al.* 1970, 17. Moore *et al.* 1976, 18. Normark 1974, 19. Plessis *et al.* 1972, 20. Roberts 1972, 21. Rona & Clay 1967, 22. Ross & Shore 1965, 23. Scholl *et al.* 1970, 24. Seibold & Hinz 1974, 25. Stride *et al.* 1969, 26. Uchupi 1968, 27. Van Andel & Komar 1970, 28. Wilhelm & Ewing 1972, a. Ballance 1964, b. Corbett 1973, c. Gregory 1969, d. Ksiazkiewicz 1958, e. Kuenen 1948, f. Laird 1968, g. Mikulenko 1967; h. Newell *et al.* 1953, i. Rupke 1976, j. Schwarz 1975, k. Smith 1970, l. Smith & Woodcock 1976, m. Spreng 1967, n. Williams & Prentice 1957, o. Williams *et al.* 1965 and p. Woodcock 1976b.

seismic profiles across present continental margins and those inferred from ancient on-land sequences. Here these two groups will be referred to informally as 'recent' and 'ancient' slides, respectively, although many of the 'recent' slides probably occurred in the Pleistocene rather than in the Holocene, and a minority in the Tertiary or late Mesozoic. The size parameters used are the average thickness of the displaced slide sheet and its average downslope width. The along-slope length is also an important independent variable; compare, for instance, the low length/width slides of Embley (1976) with the high length/width slides of Lewis (1971). However, because most seismic profiles run perpendicular to continental margins the length is often ill-defined and must be ignored here.

The thickness of ancient slide sheets is easily determined but their lateral extent is not. Only those examples where a reasonable estimate of sheet width could be made have been selected from the large literature. Even so, problems of non-exposure and later deformation mean that some estimates of ancient slide sizes may be in error by a factor of two or more. This uncertainty is too small to influence later conclusions.

The lower size limits imposed by the graph axes of Fig.

1 are not meant to imply similar limits on slide size. Some smaller ancient slides have been described (e.g. Daley 1972). The existence of these small slides, and the fact that a particular effort was made to find examples of large ancient slides, probably means that the distribution in Fig. 1 somewhat over-estimates ancient slide size.

The important feature of Fig. 1 is the non-coincidence of the fields of recent and ancient slides. The two fields do overlap, but about 67% of the recent data and over 83% of the ancient data fall outside the overlap area.

Assessing size in terms of cross-sectional slide area (Fig. 1), the recent examples range from 10^4 to 10^9 m^2, with an arithmetic mean of about 10^7 m^2. The ancient examples range from less than 10 to about 10^6 m^2, with an arithmetic mean of about 10^5 m^2. On average, therefore, the examples of recent slides are at least an order of magnitude larger in both thickness and width than described ancient slides. Why is this?

INTERPRETATION OF SLIDE SIZE CONTRASTS

The apparent absence of small recent slides is easily explained as an artifice of the seismic profiling technique. With present equipment any slide sheet less than about 5m thick would be impossible to detect (Moore 1977). The recent data on Fig. 1 therefore have a lower thickness limit at about this value.

The apparent absence of large ancient slides is more fascinating. There are two possible explanations; either large slides are preferentially developed on present margins, or the ancient analogues of large slides are unrecognised in the geological record.

There is no doubt that high Pleistocene sedimentation rates due to glacially induced lower sea-levels have produced high sediment accumulation rates and abnormally large thicknesses of sediment on present margins (Moore 1977). This phenomenon gives a plausible explanation for the high incidence and large size of slides on present margins. However, it does not explain the total absence of large slides in the ancient record. We would at least expect ancient examples immediately after other major glacial episodes in the late Precambrian, Ordovician and Permian, and also in non-glacial environments of high sedimentation rate. Therefore we must take seriously the possibility that ancient preserved examples of large continental margin slides are being misinterpreted and attributed to some other tectonic mechanism. The size distribution of ancient slides (Fig. 1) supports such a possibility, with its sharp frequency decrease above a thickness of about 20 m, about the size of a large outcrop. Perhaps this shows that field geologists are prejudiced against the possibility of submarine sliding as an explanation for allochthons thicker than outcrop scale. The point here is not simply the semantic one that large slides might have been referred to as nappes or thrust sheets or some other tectonic term. Rather, the question is why the process of submarine sliding down continental margins should be so poorly represented in the ancient record, irrespective of the geometric term applied to its final product.

If the preserved products of this process exist in the geological record how are they to be recognised?

RECOGNITION OF ANCIENT CONTINENTAL MARGIN SLIDES

The following observed or inferred characteristics of recent margin slide sheets might be recognisable in the ancient record.

(a) They comprise an allochthonous sheet or sheets.

(b) Sheet thickness may be up to 3 km and sheet width up to 500 km.

(c) The lower sheet boundary is a shear plane or shear zone.

(d) The upper sheet boundary may be a shear plane or zone if the sheet is overlain by a further slide or a sedimentary contact, perhaps showing angular unconformity.

(e) The sheets involve dominantly marine sedimentary rocks; pre-existing crystalline rocks being present only as clasts or olistoliths.

(f) The sediments usually comprise shelf edge, slope or rise facies.

(g) The sheets show high-level, low overburden deformation, possibly disorganised and gradational to certain types of mélange.

(h) The sheets show no pre- or syn-emplacement metamorphism; maximum P–T conditions being about 0.85 kb and 100° C, assuming normal geothermal gradients.

(i) Allochthons superpose shallower water, more proximal sediments, detached from their basement, over autochthonous, deeper water sediments and basement.

(j) They are apparently commonest on inactive continental margins where they would subsequently appear to be pre-orogenic or early orogenic.

These characteristics are not uniquely diagnostic, individually or collectively, of ancient margin slides but they severely constrain possible interpretations. Perhaps the main problem of applying the criteria is that original slide sheet characteristics may be obscured by later metamorphism and deformation. Slide sheets on active continental margins may be almost immediately involved in tectonic deformation—for example, by incorporation in an accretionary wedge (Moore *et al.* 1976). Those on inactive margins, the majority of observed recent slides (Moore 1977, Embley & Jacobi 1977), are mostly doomed to future subduction, transform or collision tectonics.

POSSIBLE PRE-PLEISTOCENE EXAMPLES OF LARGE SLIDES

There are many examples in the geological record of large allochthonous masses comprising marine sedimentary rocks detached from their basement. However, on closer examination most of these potential analogues of

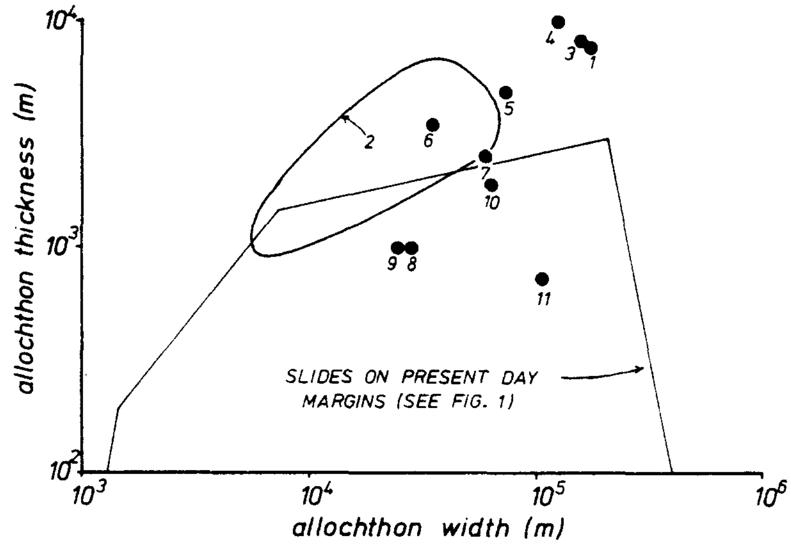

Fig. 2. Plot of average thickness against average width of some typical large sedimentary allochthons in the pre-Pleistocene record. Examples are: 1. Rockies (whole belt), 2. Rockies (single sheets) (Bally *et al.* 1966), 3 Brooks Range, Alaska, 4. Indo-Burman Ranges, 5. Pindos Zone, Greece, 6. W. Calcareous Alps (all from Spencer 1974), 7. Foothills Belt, SE Turkey (Rigo de Righi & Cortesini 1964), 8. Naukluft Mountains, Africa (Korn & Martin 1959), 9. Mamonia Complex, Cyprus (Robertson & Woodcock 1979), 10. Bobonaro Scaly Clay, E. Timor (Audley Charles 1965) and 11. Valledolmo Unit, Sicily (Marchetti 1957).

continental margin slides fail to comply with at least one of the essential characteristics listed in the last section. For instance, Fig. 2 shows the sizes of a few examples of well known, dominantly sedimentary allochthons, and demonstrates that some are considerably thicker than known continental margin slides. The Rockies thrust belt, whether considered as a whole or as individual sheets, exemplifes this case. Facies relationships disqualify many otherwise plausible examples, in that continental margin sediments are transported over shallow- rather than deep-water sediments. The Rockies, the Pindos Zone in Greece, the Foothills Belt in SE Turkey and most foreland thrust belts show this relationship. It is incompatible with down-margin sliding unless a second margin has underthrust the allochthonous margin sequence at a late stage. This might happen by collision of two opposing margins of a small ocean as in the Pindos Zone (Smith 1976), but in many foreland thrust belts the shallow-water autochthon and deeper water allochthon were demonstrably contiguous on the same margin.

Moore *et al.* (1976) suggest that some olistostrome terrains may be the equivalents of those margin slides which show a dominantly non-stratified reflection profile. This type of profile (e.g. Moore *et al.* 1976, Embley 1976, Dingle 1977) would be produced by olistostromes with relatively small clasts in a matrix. In the Bassein Slide, Moore *et al.* (1976) have also found coherent blocks of stratified sediment 'floating' on the olistostrome, and they match these to the large, kilometre scale olistoliths of some olistostrome terrains. The sizes of some Italian olistostromes are closely similar to margin slides (Fig. 2). A major difference, as Moore *et al.* (1976) point out, is again that the ancient allochthonous sequences containing marginal and oceanic rocks are emplaced onto shallow-water platform areas. However, in some Italian cases (Naylor 1978) there is a suggestion that the olistostrome was formed originally by down-margin sliding but was later thrust back onto the same margin.

One ancient terrain which does have an allochthon showing all the characteristics of a continental margin slide is the Mamonia Complex, SW Cyprus (Robertson & Woodcock 1979). The complex comprises a thin allochthonous sequence of clastic and hemipelagic continental margin sediments now resting with a low-angle tectonic contact on a local autochthon of pillow lavas with a hemipelagic sediment cover. Here, then, the allochthon was truly emplaced onto deeper water facies. The total size of the allochthon is within the range of present day margin slides (Fig. 2).

Another pre-Pleistocene example, though from a recent margin, is the series of late Cretaceous slide sheets drilled on the W. African margin at DSDP Site 415 (Leg 50, DSDP 1977, *Anon.* 1977). These involve an original stratigraphic thickness of perhaps 200 m of Upper Cretaceous continental margin sediments, now repeated up to five times by low angle faults.

The record of pre-Pleistocene slides is therefore exceedingly sparse and only serves to highlight the problems posed in this paper.

CONCLUSIONS

This paper has demonstrated the following conclusions.

(a) That submarine slides described from present day continental margins are on average several orders of magnitude larger in cross-sectional area than submarine slides described from ancient on-land sequences.

(b) That, although the apparent absence of small slides on present margins is a technical artifice, the absence of described ancient analogues of large margin slides is a real feature.

(c) That enough characteristics of recent slides can be observed or inferred to enable ancient analogues to be recognised.

(d) That, although pre-Pleistocene slides can be identified from present and ancient continental margins, they are rare.

We are left, therefore, with the dilemma of an important and well documented recent structural process which does not seem to be adequately represented in the geological record. If this paucity of described ancient slides on continental margins simply reflects unfamiliarity among field geologists with the scale and characteristics of recent slides, then perhaps this paper will stimulate recognition of some more examples. If few are discovered then we need to give more thought to why conditions on present margins are so unusual.

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