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Sequence stratigraphy, seismic profiles, and cores of Pleistocene deposits on the Rhône continental shelf

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Abstract

High resolution seismic profiles on the Rhône deltaic shelf has shown the existence of a complex of Pleistocene superimposed prograding wedges interrupted by a major incised valley system cutting across the shelf. The individual wedges are interpreted, from internal geometry and coring data, as prograding shoreface deposits accumulated during periods of relative sea level lowering punctuated by small-scale relative sea level falls or forced regressions. They are related to 5th-order glacio-eustatic cycles and are stacked to form a composite 4th-order sequence. Radiocarbon dating (Tandetron AMS) of the upper wedge (to 40 ka BP) indicates a stratigraphic hiatus across the shelf corresponding to the glacial maximum lowstand at the end of the Würmian cycle (isotopic stage 2) during which sea level had dropped to 120 m below present sea level. Seaward tilting of the wedge boundaries indicate that the shelf has been subjected to differential subsidence that provides the necessary accommodation space for deposits to accumulate on the mid-outer shelf. The seaward tilting results from a cumulative effect of sediment and hydrostatic loading. Tectonism is also expressed by a westward shore-parallel tilting in the area east of the incised valleys. The amount of tilting, the stacking pattern of the wedges, and the location of incised valleys are structurally controlled, by the alpine orogen which dips westward under the Rhône margin. The tectonic component interacts with glacio-eustatic sea level fluctuations and accounts for the partition of the shelf into two areas with specific features separated by the Rhône incised valleys.

1. Introduction

Studies of modern depositional environments provide good opportunities to test sequence stratigraphic concepts because they offer the possibility of correlating high quality seismic data with dated facies. Analysis of seismic profiles recently made on the eastern part of the Rhône shelf (Tesson et al., 1990a), has shown that Pleistocene shelf deposits form thick sediment wedges which have been identified as 'shelf-perched lowstand wedges' as defined by Posamentier and Vail (1988). Similar Late Pleistocene shelf deposits have been described in other areas (Berryhill, 1986; Suter et al., 1987; Kindinger, 1988; Field and Trincardi, 1991; Aksu et al., 1992), but until now, studies have been based mainly on analysis of seismic data without accurate dating control, except for post-glacial deposits. In this study we present the results of regional seismic analysis supplemented by faciologic and absolute chronological data from Kullenberg cores positioned along seismic lines. Integration of these complementary data enables us to refine the previous interpretations

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and provides new data concerning relative sea level variations and factors controlling Late Quaternary sedimentation.

2. Regional setting

The Rhône shelf, located off the French coast between the Pyrenean and Alpine orogenic belts in the northwestern part of the Mediterranean Basin, forms a crescent-shaped platform about 250 km long and 75 km wide (Fig. 1a). This shelf is relatively flat and slopes gently seaward to the shelf break located at a depth of 120 to 130 m. The shelf-slope break is very irregular and incised by numerous canyons and shelf-edge slumps (Coutellier, 1985). This shelf is part of a young passive margin resulting from a Oligo–Miocene rifting phase followed by a period of oceanic accretion that opened the Provençal Basin. The post-rift history is characterised by accumulation of a thick wedge (900 m at the inner shelf, 1900 m at the outer shelf) of clastic sediments since the Upper Miocene time and the progressive outbuilding of the shelf which has onlapped against the uplifted tectonic zones on the east and west extremities of the area (Bessis, 1986).

3. Nature of deposits

3.1. Seismic data

A regional grid of 3000 km of high resolution seismic profiles (Minisparker, 50 J) was obtained over the Rhône shelf between 1989 and 1993 (Fig. 1b). The records reveal the existence of several major features (Tesson et al., 1990a,b):

(1) A large incised valley system, with discontinuous seismic reflectors, cuts across the shelf west of the present mouth of the Rhône (Fig. 1a). This system, 15 km wide, extends seaward into a major shelf edge canyon (Petit Rhône canyon) which incises the outer shelf and slope. Conventional multichannel seismic profiles indicate that these Rhône fluvial incisions, up to 1500 m deep, were successively used during Late Tertiary and Quaternary low sea level stands and served as a sediment conduit for a large basin floor fan (Lefebvre, 1980; Droz, 1983).

(2) Shelf deposits on both margins of the incised valley (Fig. 2) occur as a complex of superimposed

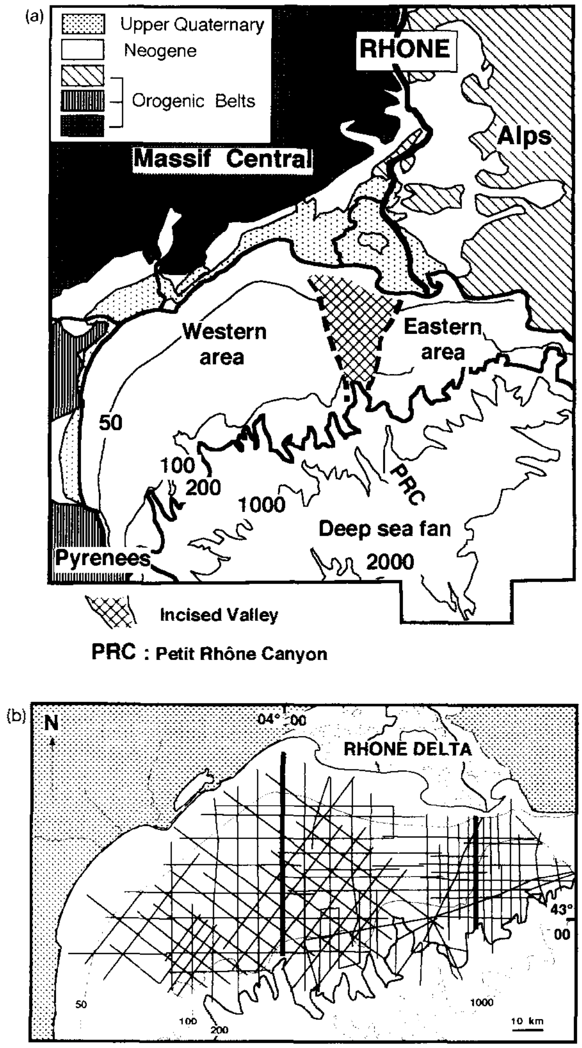

Fig. 1. (a) The Rhône Margin, regional setting. (b) The regional grid of seismic lines. Darkened lines refer to the two sections depicted in Fig. 2.

prograding wedges that thicken seaward (up to 200 m at the shelfbreak), pinch out landward and onlap onto the mid-shelf at a depth more than 90 m below present sea level. At least six individual superimposed wedges can be observed above the seismic multiple. Each wedge is composed of seaward prograding clinoforms (maximum dip of 1.5°) and comprises lozenge-shaped subunits separated by oblique internal erosion surfaces. Each prograding wedge is bounded by a basal downlap surface and an upper toplap surface. The toplap surface is locally incised

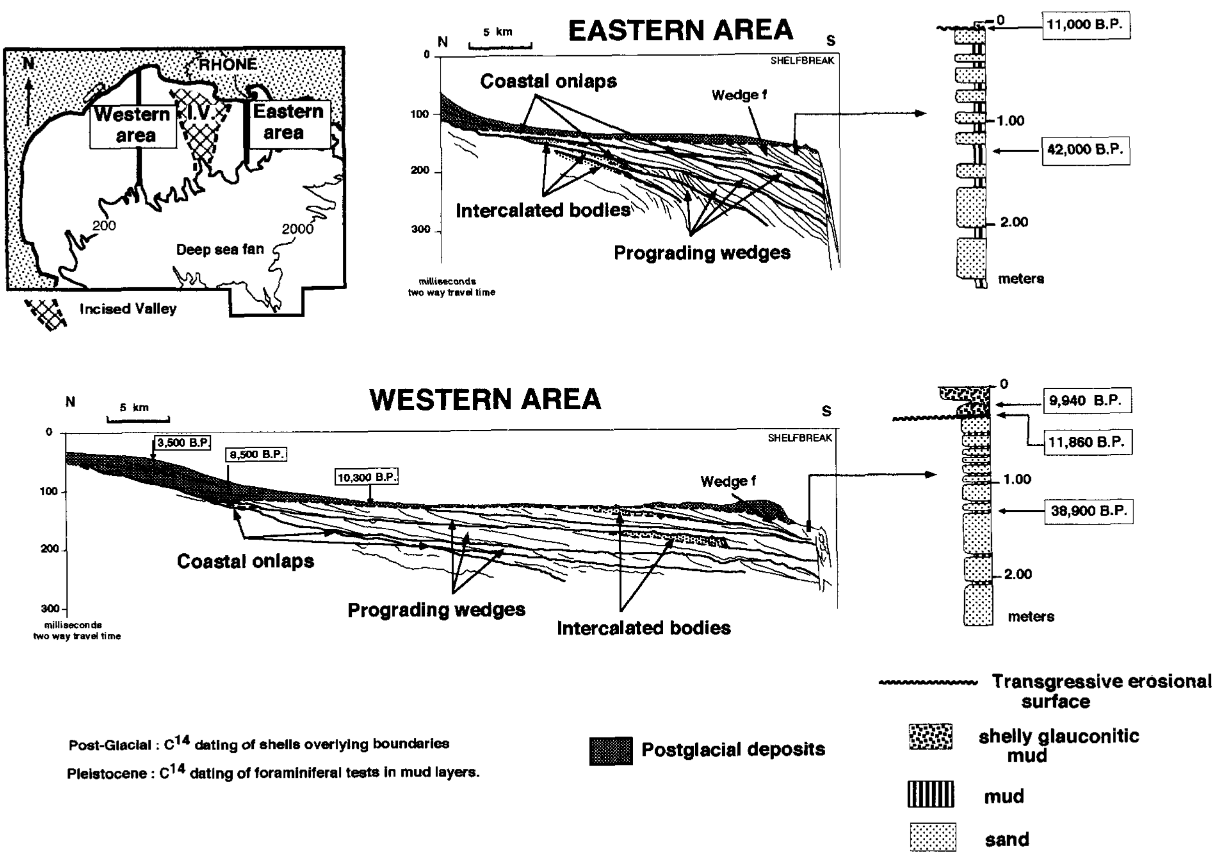

Fig. 2. Line drawing of two seismic profiles showing general setting of Late Quaternary deposits (see Fig. 1b for location). Location, lithology and chronology of Kullenberg cores.

by small channel features (0.5 km wide, 10–15 m deep) filled by deposits with discontinuous reflectors which onlap onto the channel walls.

(3) The uppermost wedge is cut by an erosional surface overlaid by a set of progradational bodies, 20 to 30 m thick, backstepping landward and well developed on the outer and inner shelf. They are overlain, near the present coastline and on the adjacent deltaic plain, by modern coastal plain deposits forming a regressive wedge (Oomkens, 1970).

All individual wedges and their bounding surfaces are regionally continuous and can be traced over the entire shelf, but the geometry and stacking pattern are different on either side of the incised valley (Fig. 2).

The prograding wedges in the eastern area are directly superposed, and the downlap surface generally coincides with the toplap surface of the underlying wedge. Locally, however, small units, 4 to 5 m thick, are intercalated on the mid-shelf at the updip part of the wedges. The onlap terminations of the successive wedges migrate either landward or seaward, and form a complex saw-toothed vertical pattern (Tesson et al., 1993). Moreover a westward shelf parallel tilting towards the incised valley is superimposed on the regional seaward tilting (Tesson and Allen, 1995).

The prograding wedges in the western area are separated, on the mid-outer shelf, by intercalated units forming isobath parallel elongate bodies, up to 35 m thick. These intercalated units show high angle clinoforms (up to 7°) or chaotic seismic facies resting on a rectilinear erosional surface on the top of the underlying prograding wedge. The seaward tilting intensity is less important than in the eastern area and the onlap terminations of the wedges are mainly located at the inner shelf.

3.2. Core data

A set of Kullenberg cores (10) were taken on the outer shelf, on both sides of the incised valleys system in areas where postglacial deposits are reduced and constitute a condensed section (Gensous et al., 1993b). Core positions were accurately located from seismic data. The presence of a surficial coarse stratum (shell debris) and the firmness of underlying deposits limited core length sampling up to 3 m but a complementary sub-bottom profiler survey (3.5 kHz) was carried out prior to coring to enhance correlations between seismic and lithologic data (El Hmaidi, 1993).

From base to top of the cores we observed two sections separated by an erosional surface (Fig. 2):

(1) A lower section, correlated on seismic lines to the uppermost prograding wedge (f). In the eastern area, sediments cored include interbedded sand, mud and silt layers of centimetric to decimetric thickness; sand layers present a sharply defined base. In the western area, deposits consist of very fine sand to silt units (decimetres thick) that alternate with dark silty clay laminae. The lithology and microfaunal species (foraminiferas and ostracodes) indicate, in both areas, a deposition in a shallow marine (lower shoreface to inner shelf) environment (El Hmaidi, 1993). Radiocarbon dates (A.M.S. Tandetron) were obtained for foraminiferal tests collected in the undisturbed upper part of wedge f on two selected cores located on both sides of the incised valley and these indicate ages of ≅40 ka BP (Gensous et al., 1993a).

(2) An upper section comprises a coarse-grained shelly layer dated 12 to 10 ka BP (El Hmaidi, 1993). This rests on an erosional surface and is capped by a fine stratum of shelly beige mud (10–20 cm) with pelagic microfauna.

4. Stratigraphic interpretation

Seismic data show that the stack of prograding wedges forms an overall regressive system, which resulted in progradation of the shelf. The individual wedges were interpreted as prograding shoreface deposits that accumulated during a period of lower sea level on the basis of internal structure, present bathymetry (>90 m) and location of coastal onlaps at the mid-shelf (Tesson et al., 1990a,b). The complex of wedges represents a 'shelf-perched lowstand prograding wedge complex' (Posamentier and Vail, 1988). Internal erosional surfaces represent successive downward shifts of coastal onlaps and indicate that progradation occurred under conditions of 'forced regressions' (Posamentier et al., 1992) in response to small-scale episodic relative sea level falls.

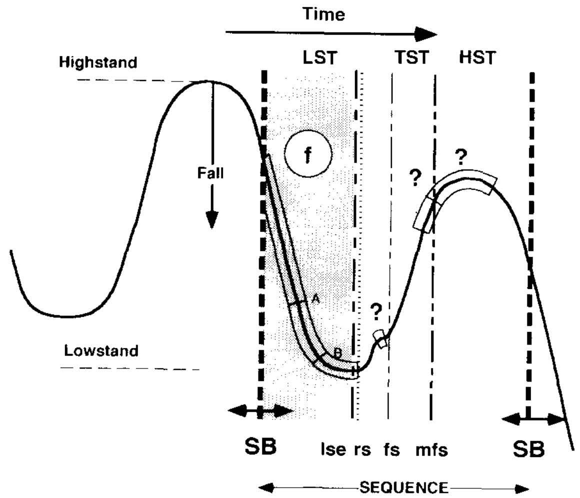

Fig. 3. Trace of the chronological framework of lowstand prograding wedges related to relative sea level variations. *LST* = lowstand prograding wedge; *TST* = transgressive systems tract; *HST* = highstand systems tract; *SB* = sequence boundary; *lse* = lowstand surface of erosion; *rs* = ravinement surface; *fs* = flooding surface; *mfs* = maximum flooding surface; *f* = uppermost wedge of the lowstand complex; ? = units intercalated between prograding wedges; *A*, *B* = subunits inside lowstand wedge.

The toplap surface of the wedges is composed of two types of surfaces (Fig. 3):

(1) A subaerial erosional surface associated with relative sea level fall during progradation of the wedges (lowstand surface of erosion). The erosional channels which incise the upper surface of the wedges represent distributary channels associated with successive step-like lowering of sea level.

(2) An erosional flooding surface resulting from wave erosion during subsequent relative sea level rise (ravinement surface).

These two surfaces generally merge, except at channel incisions. There, the lowstand surface of erosion occurs at the base of the channel whereas the ravinement surface cuts the top of the channel fill.

The intercalated bodies, positioned at the mid-outer shelf in the western part of the study area, are interpreted as nearshore sand bodies resulting from transgressive erosion and longshore transport of underlying lowstand wedge deposits during episodes of relative sea level rise that occurred between periods of wedge progradation (Gensous et al., 1993b).

The deposits overlying the uppermost wedge (unconformity) represent post-glacial deposits (post-18 ka BP) and are outside the scope of this paper. The backstepping progradational units on shelf represent parasequences of the transgressive systems tract (Gensous et al., 1989). They are overlain by the highstand deposits of the modern Rhône delta which, as many deltas all over the world, has prograded since the period of deceleration of sea level rise during the Early to Middle Holocene (L'Homer et al., 1981; Stanley and Warne, 1994).

Lithologic and microfaunal data from cores reveal that preserved deposits at the top of the prograding wedge f are lower shoreface to inner shelf deposits, and which is in agreement with a previous interpretation from seismic facies (Tesson et al., 1990a). They indicate that erosion of wedges during relative sea level fall (subaerial erosion and channel incision) and subsequent relative sea level rise (erosional shoreface processes) was moderate and removed only the more proximal deposits (upper shoreface and beach sands) that had accumulated above the fair weather wave base. These data also confirm that wedges accumulated during periods of relative sea level lowstand because, if progradation had occurred during highstand conditions, the subsequent sea level drop of several ten metres amplitude would have led to intense erosion of the wedges and preservation of only the more distal shelf mud and silt facies (Tesson et al., 1993).

The shelly stratum (dated from 12 to 10 ka BP), overlying the erosional wave-ravinement surface at top of wedge f, represents a lag deposit associated with post-glacial sea level rise.

The superficial hemipelagic mud sheet on the mid-outer shelf is a condensed section which is time correlative with late transgressive and highstand parasequences deposited on the inner shelf and deltaic plain (Gensous et al., 1993b).

5. Discussion

It is assumed that high frequency/high amplitude glacio-eustatic variations (Milankovitch cycles) have been the main factor controlling stratigraphic organization of Pleistocene deposits. The Quaternary sea level curve is derived from oxygen isotope variations of deep sea sediment (Chappell and Shackleton, 1986). These record changes in global ice volume, and can be calibrated with studies on coral terraces such as those of Barbados and New Guinea (Moore, 1982; Bard et al., 1990). In most studies dealing with shelf areas, correlation of Quaternary depositional units with glacio-eustatic sea level fluctuations is problematic because the absolute age of depositional units is generally unavailable, except for post-glacial deposits. The upper shelf unconformity is, as a rule, assumed to record the late Würm Period lowstand surface and the underlying sequence boundaries are correlated, counting back, with the successive glacial maximum lowstands. The ages assigned to depositional units vary according to the glacial model used (number, magnitude and frequency of glacio-eustatic cycles) and the preservation potential supposed (Berryhill, 1986; Suter et al., 1987; Kindinger, 1988; Aksu et al., 1992).

It was initially proposed from seismic data (Tesson et al., 1993) that lowstand prograding wedge complex on the Rhône shelf formed during the latest (Würm) fourth-order glacio-eustatic cycle lowstand, and that individual wedges could represent progradation associated with 5th-order glacio-eustatic cycles. Radiocarbon dating (to 40 ka BP) of the uppermost prograding wedge (f) (Fig. 4) supports this interpretation: it accumulated during isotopic stage 3 (5th-order cycle) which is part of the Würm glacial period (4th-order cycle). Ice sheet volume increased by steps punctuated by stillstand periods during this period beginning after interglacial stage 5e (122 ka BP). At isotopic stage 3, sea level was about tens of metres below present sea level. Recent data from Bard et al. (1990) indicate that sea level was 80 m below present sea level and that lowstand conditions prevailed. Moreover, absolute dating also shows that glacio-eustatic cycles are not all recorded on shelf deposits. An important stratigraphic hiatus, corresponding to isotopic stage 2, exists between the upper prograding wedge f and the overlying post-

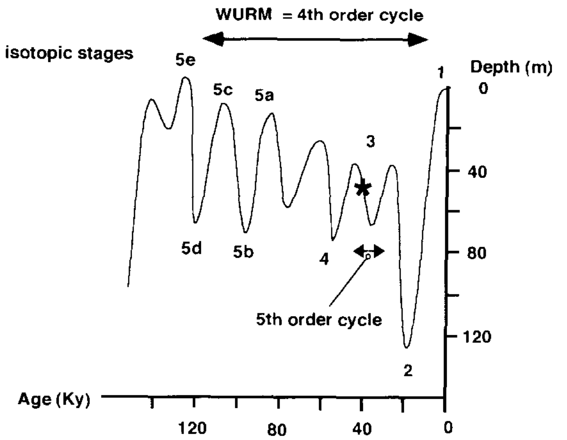

Fig. 4. Curve of glacio-eustatic variations during the last glacial Würmian cycle as deduced from the isotopic record (after Pinter and Gardner, 1989). *2, 3, 4, 5a, 5b, 5c, 5d, 5e* = isotopic stages; star indicates dating of upper wedge f.

glacial deposits (post 18 ka BP). Isotopic stage 2 marks the glacial maximum lowstand at the end of the Würmian cycle during which sea level had dropped to 120 m below its present level. Two hypotheses, which are not mutually exclusive, may be advanced to explain the sedimentary hiatus on the shelf: (1) the important eustatic drop induced a shifting of the shoreline and depocenter seaward off the previous shelf break (non-depositional hiatus); or (2) on-shelf erosion, intense during the sea level fall and subsequent transgression, removed previous lowstand deposits (erosional hiatus).

Consequently, the erosional discontinuity at top of wedge f marks the maximum lowstand associated to deep water fan sedimentation at the end of the Würmian period. The overlying postglacial deposits constitute the transgressive and highstand systems tracts of this 4th-order cycle.

Geometry and stacking pattern of the wedges indicate that differential subsidence, in addition to glacio-eustatic oscillations, controls regional stratigraphy. Wedge boundaries show seaward dipping angles, increasing with the age of the wedge. The complex of prograding wedges shows an overall aggradational and progradational stacking pattern, whereas the Quaternary sea level curve records a regular downward shift during Würm time. This implies that the shelf has been subjected to a progressive seaward tilting that provided the necessary accommodation space for deposits to accumulate on the mid-outer shelf. Tesson and Allen (1995) have shown that this tilting occurs at the same time scale as the high frequency glacio-eustatic fluctuations. It results from a cumulative effect of sediment loading at the end of lowstand wedge progradation and hydrostatic loading during subsequent transgressive periods. The intensity of tilting, which determines the different stacking pattern and position of coastal onlaps, decreases westward of the Rhône incised valley. It is related, via the location of the hinge line, to a structural control exerted by the Alpine orogen dipping westward under the Rhône margin (Tesson et al., 1993). Likewise, the westward tilting of the eastern shelf area may be related to the activity of a N–S extensional fault zone that constrained the location of the Rhône incised valley during each relative sea level lowering since the Early Pliocene (Tesson and Allen, 1995).

6. Conclusions

(1) Late Quaternary deposits of the Rhône shelf have accumulated as a complex of stacked progradational wedges bounded by regional unconformities and interrupted by a large incised valley system cutting across the shelf.

(2) The individual wedges represent shoreface deposits which have prograded on the shelf during periods of relative sea level lowering punctuated by small-scale relative sea level falls or 'forced regressions'.

(3) They are related to 5th-order glacio-eustatic cycles and stacked so as to form a composite 4th-order sequence

(4) Radiocarbon dating (to 40 ka BP) of the uppermost wedge points out that the maximum lowstand at the end of the Würmian period (isotopic stage 2) corresponds to a shelf stratigraphic hiatus associated with basinward shift sedimentation.

(5) A regional seaward tilting of the wedges has provided the necessary accommodation space for deposits to accumulate and to on the mid-outer shelf. It is attributed to sediment and hydrostatic loading during late lowstand and transgressive periods.

(6) The intensity of tilting, which decreases westward, determines the stacking pattern of prograding

wedges. It is related to a structural control exerted by the alpine orogen which also constrained the location of incised valleys. It results in the partition of the shelf into two areas with specific growth patterns.

(7) This paper shows evidence of tectonic control over the genesis and stratal patterns of Quaternary shelf deposits related to high frequency glacio-eustatic cycles. According to the ratio subsidence rate versus eustatic fall rate, stratigraphic organization can locally varies (Posamentier and Allen, 1993) and some glacio-eustatic cycles are not necessarily recorded on the shelf. Correlations between seismic units and glacio-eustatic cycles is hazardous without regional stratigraphic insight constrained by accurate absolute dating of sedimentary units. The application of sequence stratigraphic concepts to locally restricted systems does not allow to distinguish between local (autocyclic) and global (allocyclic) controlling factors and can lead to wrong and/or incomplete stratigraphic correlations and interpretations.

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