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Reflected sediment gravity flows and their deposits in flysch of Middle Dalmatia, Yugoslavia

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ABSTRACT

The Eocene flysch of Middle Dalmatia comprises several beds that are interpreted to have been deposited from reflected sediment gravity flows. Their compositions are similar and two bed types are differentiated: complex beds that are debrite-plus-turbidite couplets, and turbidites.

The sequence alternations in the turbidite part of the bed, opposing ripples within the same bed, and opposite flow directions indicated by flutes and ripples are indicative of flow reflections. The influence of seiches is suggested by the occurrence of symmetrical (oscillation) ripples.

The palaeotransport directions of reflected flows show wide dispersal. A geometry of small, fault-controlled sub-basins with centripetal palaeotransport patterns is proposed.

INTRODUCTION

The Eocene deep-marine clastics studied are situated in the environs of the cities of Split and Solin in Middle Dalmatia (Fig. 1). The outcrops are limited, mainly due to intensive urbanization and land cultivation. We have therefore collected our data from some very well exposed parts of the coastline, and from some limited exposures inland.

In an attempt to analyse the evolution of the Middle Dalmatian basin, particular interest was paid to the palaeotransport directions because previous data indicated a rather simple palaeodirectional pattern in the explored area (Marinčić, 1981) with only longitudinal flows. In most cases palaeotransport directions were investigated using ripples, orientations, imbricated marl chips, and flute marks that are developed on a few thin beds. The number of readings is rather small due to the poor quality of the exposures caused by weathering. However, considerable effort was made to recognize properly weathered ripples and cross-laminations that were large enough for field measurement, and to enlarge some small and badly weathered ones by chiselling. All measurements were corrected on the stereonet for local tectonic dip and axial plunge of folds both being variable over the area (Fig. 1B).

The early phase of basin analysis (Marjanac, 1986) indicated the occurrence of megabeds that originated from ponded sediment gravity flows. The further exploration (Marjanac, 1988a,b, 1989) documented several megabeds that originated from reflected sediment gravity flows—these are the subject of the present paper.

AGE AND SEDIMENTARY SEQUENCE

The basal contact of flysch is visible on the northern flanks of Marjan Peninsula where it overlies cherty foraminiferal limestones (alveolina and nummulite limestones) (Kerner, 1903, 1914) and 'transitional' calcarenites with glauconite (Šikić, 1968; Magaš & Marinčić, 1973). The age of the foraminiferal limestones has been determined as Cuisian and early Lutetian (Magaš & Marinčić, 1973), but Chorowicz (1977) quotes a middle to late Lutetian age. Macroforaminifers indicate that the overlying flysch is of late Lutetian to late Eocene age (Blanchet, 1972; Magaš & Marinčić, 1973), and possibly even partly Oligocene

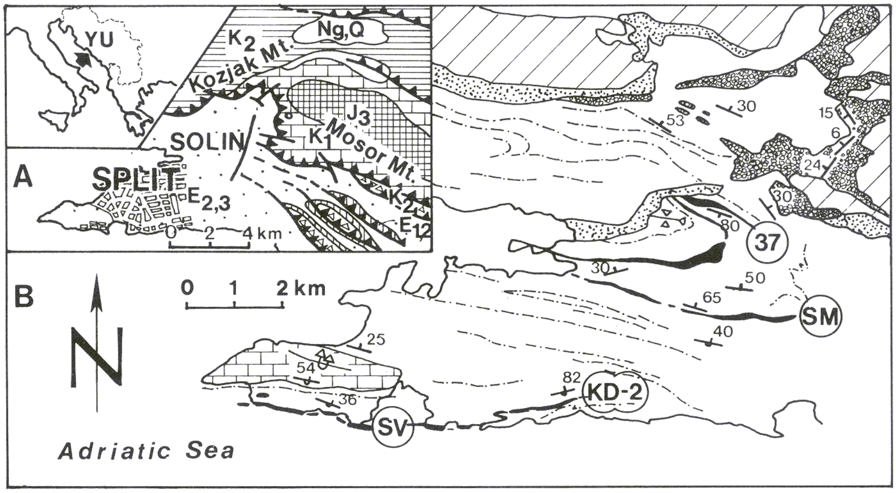

Fig. 1. Location of area studied. (A) General geological map of Split hinterland after Blanchet (1975) with cities of Split and Solin added. (B) Lithofacies map after Kerner (1914), simplified and modified. Megabeds described in this paper are represented by solid lines, and stipple patterns indicate other megabeds in this area. For key to lithologies see Fig. 2.

(Blanchet, 1975), but calcareous nannofossils indicate a late Lutetian to middle Priabonian age—NP 17 to NP 19 nannofossil biozones (Benić, 1983). On the southern flanks of the Marjan Peninsula flysch is in tectonic contact with Eocene cherty foraminiferal limestones as well as 'transitional' glauconitic calcarenites, and on the northwestern slopes of Mosor Mountain (Fig. 1A) it interfingers with mass-flow dominated coarse-grained fan deltas.

The flysch of the Split region was studied in detail by Kerner (1903), who divided the succession into three broad depositional units: the lower, the middle and the upper flysch zones.

The lower flysch zone is generally poorly exposed, so the whole sequence is not accessible, except for thicker beds that are well exposed in the field. The number of thick turbidite beds (thicker than 10 m) is rather large. Kerner's middle flysch zone is represented by a single-event olistostrome (Marjanac, 1985, 1986, 1987). The upper flysch zone is sandier with a general increase of coarse-grained sediments and sandy marls. Detailed facies analysis of the upper flysch zone is given by Marjanac (1986).

The present paper deals mainly with megabeds of a part of the lower flysch zone, and a part of the upper flysch zone. Their locations are indicated in Fig. 1(B). Such organization of the flysch suite led Grubić & Komatina (1962/63) to recognize a 'marly' and 'sandy development' of flysch.

SEDIMENTATION DEPTH

Unfortunately only negative evidence is available for a deep-water origin of flysch sediments in this region. A sequence of flysch over 1500 m thick was deposited in different depths, but generally below the storm wave base. Only a part of the upper flysch zone that interfingers with fan deltas was probably deposited in shallower depths, but there is at present no evidence of storm or tidal activity. The macrofossil fauna in the flysch is allochthonous, resedimented or just transported, and thus cannot indicate any depth range. Ichnofossils are rare in sediments of deep-water origin, but are more abundant in stratigraphically younger sediments of shallower-water origin (rare Zoophycos and Gloeckeria occur, so these sediments should be considered of sublittoral to bathyal origin; Frey, 1975).

BED TYPES

Complex beds

Complex beds (Marjanac, 1986) are couplets of debrite in the lower part and turbidite in the upper part of the bed. The thickest bed of this type is the 170-m-thick Kamen–Sutikva olistostrome described elsewhere (Marjanac, 1985, 1986, 1987). The 'SV' megabed outcrops for 5 km along the coastline near Split and

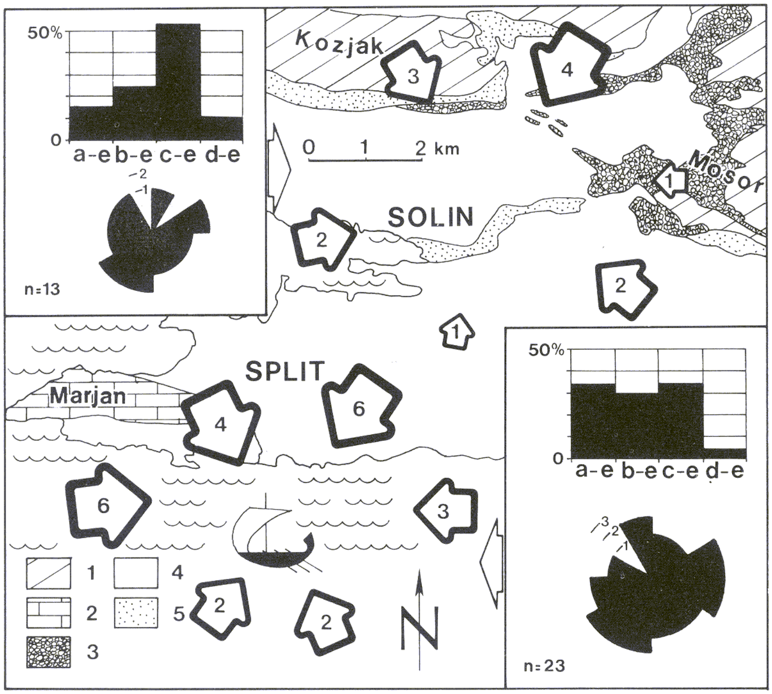

Fig. 2. Palaeotransport directions of turbidites in the study area showing centripetal symmetry. The arrow size and numbers indicate number of flows. The map inserts show the distribution of Bouma-sequences and palaeocurrents for the Solin (upper left) and Split (lower right) areas. Note the differences in distribution of Bouma-sequences and palaeotransport directions between Solin and Split. Key: (1) pre-Palaeogene carbonates (predominantly Cretaceous), (2) Palaeogene carbonates (foraminiferal limestones), (3) Palaeogene coarse-grained clastics (fan deltas of Mosor Mountain), (4) Palaeogene flysch, (5) Quaternary sediments. Simplified map after Kerner (1914).

its inland prolongation is designated as 'KD-2' (Fig. 1B). It consists of a $\leqslant 14$-m-thick debrite and > 32-m-thick normally graded turbidite (the turbidite marl cap is unexposed so the total thickness is unknown) (Fig. 3). The base of the SV megabed rests on slumped fine-grained sediments, but their genetic relationship is not clear. The debrite is matrix-supported with well rounded limestone clasts up to 1 m across. Detritus consists of Upper Cretaceous recrystallized limestone boulders with occasional rudistid fragments, light coloured limestone boulders with corals (K_2 age?), clasts of Eocene foraminiferal limestones and clasts of Eocene calcarenite with glauconite. In the upper part of the debrite, pebble- to cobble-sized, unrounded limestone clasts prevail, and the matrix content is considerably reduced compared with the lower part. The contact of the turbidite and debrite is very irregular due to the presence of 18-m-high mushroom-shaped debrite intrusions that penetrate through the turbidite. The intruded sediment consists of coarse-grained (pebble size) lithic debris and marly matrix with scattered large nummulitids and locally abundant marl chips (some up to 0·5 m long) that are sometimes imbricated. This sediment has a transitional contact with the host sediment, composed of packed rudite to coarse-grained calcarenite. The coarse-grained sediment of the upper part of the bed also contains a 1-m-long, parallel-laminated, fine-grained arenaceous clastic dyke and several large oyster shells. The turbidite displays parallel lamination, ripples, occasional climbing ripples and convolute lamination. Structures are organized in alternating sequences of massive, parallel-laminated and rippled arenite; and alternating sequences of massive and parallel-laminated arenites. Ripples indicate flow reversals in a few levels within the turbidite, with transport directions towards the northwest and southeast, respectively (Fig. 4).

The 14-m-thick bed 'SM' has well-exposed superimposed ripples (Fig. 5); short wavelength forms are superimposed on straight-crested current ripples with

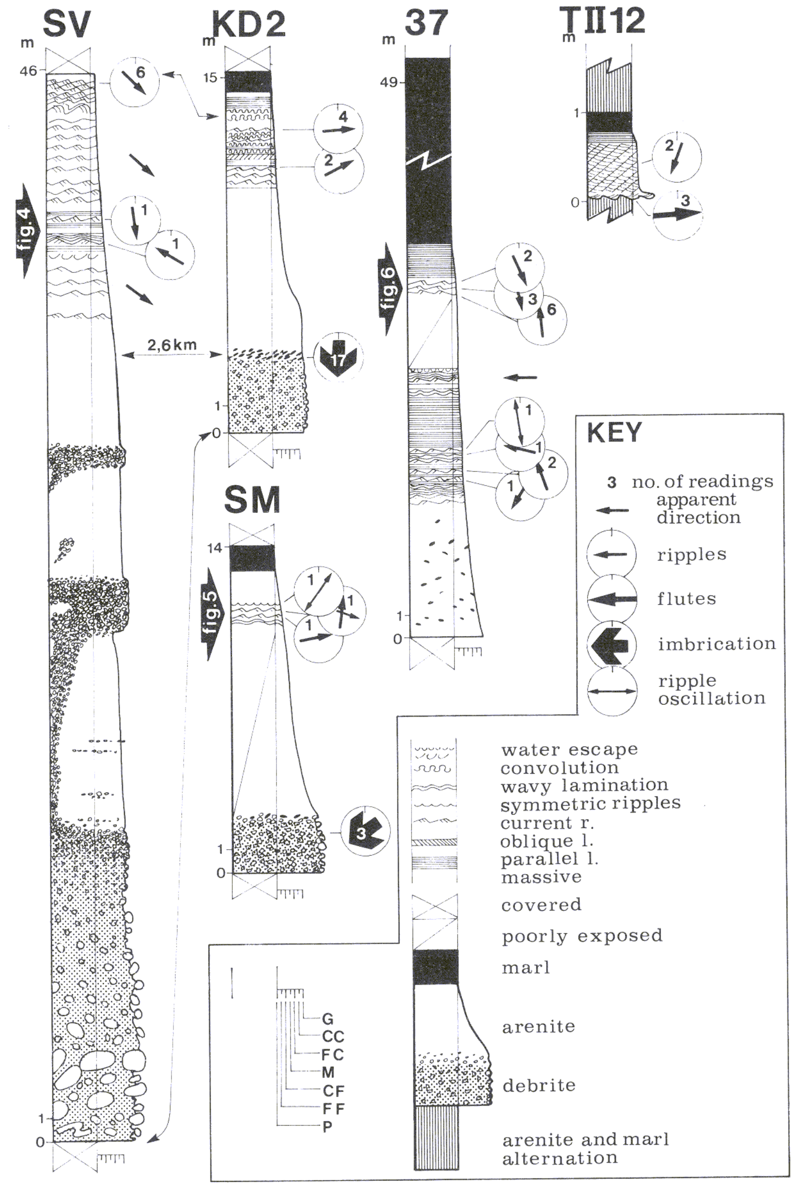

Fig. 3. Pluridirectional beds exposed in the study area. The locations of beds are shown in Fig. 1(B), and position of type sections in Fig. 7. The SV–KD-2 bed is exposed along 5 km of coastline, beds 37 and SM are exposed for more than 4·5 km but the type sections offer the best exposures. Grain sizes: P = pelite; FF, CF, M, FC, CC = very fine, fine (upper), medium, coarse (lower) and coarse-grained arenite, respectively; G = gravel.

double the spacing (0·3 m). The main palaeotransport direction is towards the north and superimposed ripples indicate a southeastward flow direction. Higher in the bed there are symmetrical (oscillation) ripples that indicate NE–SW oscillation; the ripple spacing is 0·28 m.

Turbidites

Turbidites of this type are both thick (> 10 m) and rather thin (< 1 m), and are capped by marls of varying thickness. Because the thickness of marls was one of the criteria for adopting the term 'contained

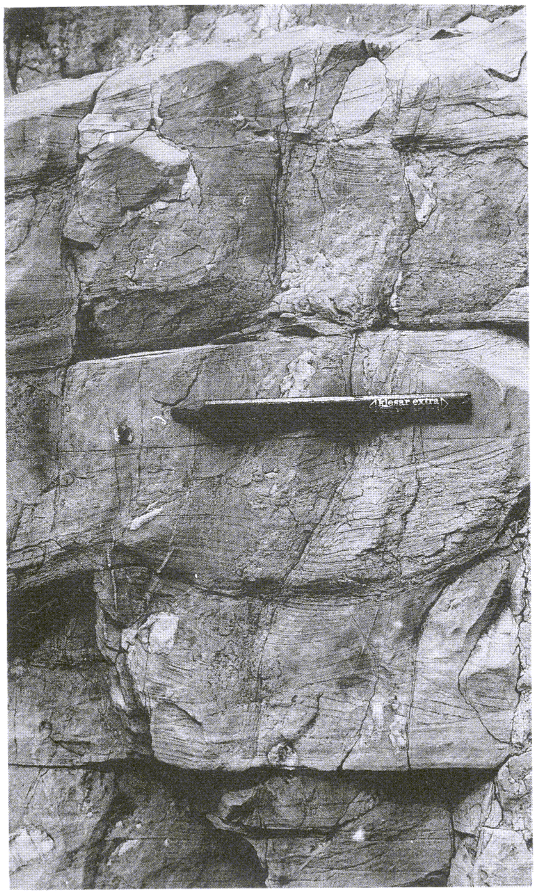

Fig. 4. Detail of the SV megabed. The ripples in the lower unit indicate a flow direction opposite to that from ripples in the upper unit. Each unit is massive in the lower part and rippled in the upper part. The reverse flow was erosive but no bedding planes were developed. There is no grain size contrast, nor do clasts of the underlying unit appear anywhere along such contacts. Note that laminae have been highlighted by pencil in order to exaggerate the contrast. Pencil length = 15 cm.

Fig. 5. Superimposed ripples of the SM megabed. The ripple length of the older ripple set is 0·3 m, and the transport direction was towards the lower right. The superimposed ripple set has a ripple length of 0·14 m and transport direction towards the left.

turbidites' by Hiscott & Pickering (1984), and because some of the observed beds that originated from the reflected turbidity currents are rather thin (but some are very thick), this term does not seem entirely appropriate in this case.

The typical *thin* turbidite that originates from the reflected flow is bed 'TII12' that displays roughly opposite flow directions as indicated by flutes and climbing ripples (Fig. 3).

The typical *thick* turbidite of this kind is bed '37' briefly described by Marjanac (1988a). This bed displays both flow reversals, as indicated by well-exposed straight-crested ripples (Fig. 6) with palaeotransport directions towards the north and south, respectively, and sequence alternations. The bed is 49 m thick including a 32·5-m-thick marl cap (Fig. 3). The initial palaeotransport direction is *probably* towards the southwest although the lower bedding plane is unexposed. The turbidite has composite organization with alternations of massive, parallel-laminated and rippled arenites, then rippled and parallel-laminated arenites, etc. The flow reversals are obvious due to locally good exposures with the straight-crested ripples facing in opposite directions (Fig. 6). The ripple lengths in these cases are 0·5 and 0·42 m.

The very similar Contessa megabed was described by Parea & Ricci Lucchi (1975), Ellis (1980) and Ricci Lucchi & Valmori (1980), while other beds with similar composition are described by Dżułyński & Walton (1965), Hiscott & Pickering (1984), Pickering & Hiscott (1985), Bourrouilh (1987), Labaume, Mutti & Seguret (1987), Souquet, Eschard & Lods (1987), and Larue & Provine (1988).

Fig. 6. The opposing ripples of the 37 megabed. The wavelength is 0·5 m.

SEDIMENTARY PROCESSES

Complex beds were deposited by a range of sedimentary processes: (i) debris flows, and (ii) high-density turbidity currents that followed closely after or evolved from the debris flow as suggested experimentally by Hampton (1972). Deposition of the turbidite must have been very rapid to account for the trapping of pore water in the underlying debrite, load-induced liquefaction, and production of large load casts and injection structures. Some inclined injection structures indicate that some movement of sediment (sliding?) still occurred after the disturbance of the sediment interface took place. The directional characteristics of structures in the upper part of the turbidite, as well as the sequence of structures, indicate that the flow suffered changes of flow regime as well as directional changes.

A surging flow could cause the flow regime changes, but such a flow would not affect the transport direction. The direction changes could result from flows with a 'braided' pattern where individual lobes would intersect each other's path at a certain point. A flow in an unrestricted environment will expand and individual lobes should diverge from each other, thus preventing a 'braided' direction pattern from forming. However, entering a restricted basinal environment, a part of the flow or a lobe may be rebounded or reflected from one of 'walls' and thus a part of the flow may suffer a change of direction, possibly intersecting another part of the same flow. So the explanation of reversed ripples and other indicators of flow reversals would be the reflection of turbidity currents (as shown by Pickering & Hiscott, 1985, elaborated on by Pantin & Leeder, 1987, and observed during early experiments by Dżułyński & Walton, 1965). If flow reversals are the cause of the opposing ripple directions, it should be possible to estimate the locations of submarine obstacles. The flow reversal in bed TII12 could be the result of a rather local flow reflection. The ratio of the flow volume to the area of deposition is rather small, so that the resultant bed is rather thin. Pantin & Leeder (1987) concluded that it is not likely that a flow will sustain more than one reflection, but the experiment they conducted was with an extremely low density difference between the flow and the ambient fluid; with significantly greater density differences, multiple flow reversals are more probable.

The thick lutites of the megabeds were deposited from ponded turbidity current tails, and represent 'contained' turbidites.

Peculiar superimposed ripples that were observed in a few cases (i.e. bed SM) may have been generated as the main body of the flow, still moving in the 'original' direction, collided with a flow generated by the sideways reflection of the turbidity current head; a recent analogy is described by Van Andel & Komar (1969).

Symmetrical ripples are quite puzzling in turbidites. Bourrouilh (1987) tried to explain similar examples as resonance ripples. However, true oscillation is needed for the formation of such symmetrical bed forms. Possible explanations are a seiche-like oscillation (cf. Van Andel & Komar, 1969), or (more likely) seismic oscillations that affected the water mass near the basin floor.

PALAEOTRANSPORT DIRECTIONS

Recent exploration (Marjanac, 1988b) has indicated that the palaeotransport pattern in Eocene flysch around the Adriatic is rather diverse, with significant differences even in such small areas as the environs of Split and Solin (Fig. 2).

As turbidity currents flow down the slope, the resulting turbidites bear structures of a single palaeotransport direction, unless the flow suffers reflections. Some more powerful flows can flow alongslope or even upslope (see Pantin & Leeder, 1987), so that palaeotransport direction *per se* does not necessarily indicate the basin axis nor the dip of the slope. The upslope and alongslope palaeotransport directions are recorded on the western flanks of Mosor Mountain; here the mass-flow dominated fan deltas indicate the strike of the palaeoslope. Reflected turbidity current deposits, however, have structural evidence of different flow directions, roughly opposite, that can indicate the strike of morphological obstacles within the basin.

Bed TII12 is a simple case, with just one flow reflection, but a suite of mutually opposite flow indicators such as ripples indicates multiple reflections of some turbidity flows. These more complicated beds bear complex information on basin geometry, and it should be possible to infer at least a crude basin shape (and dimensions?) from just one such bed, having all the relevant field observations and adequate theoretical background.

Figure 7 shows the palaeotransport directions indicated by deposits of reflected flows, and possible locations of intrabasinal obstacles that reflected the flows. The northern obstacle seems to correspond to a part of the Kozjak structure, and the one which is a rough continuation of the Marjan anticline represents the boundary between the two depocentres in this area. These results suggest the need for separate palaeotransport direction analysis for the Split and Solin environs. Turbidite palaeotransport directions are presented in Fig. 2, with current roses in the map inserts. Two depocentres are recognized with roughly centripetal palaeotransport patterns.

According to the approximate positions of obstacles that caused the postulated flow reflections, an interpreted palaeogeological map is constructed (Fig. 8) showing two faulted blocks that formed restricted subbasins. The positions of faults is approximate, and the map lacks restoration due to the tectonic compression.

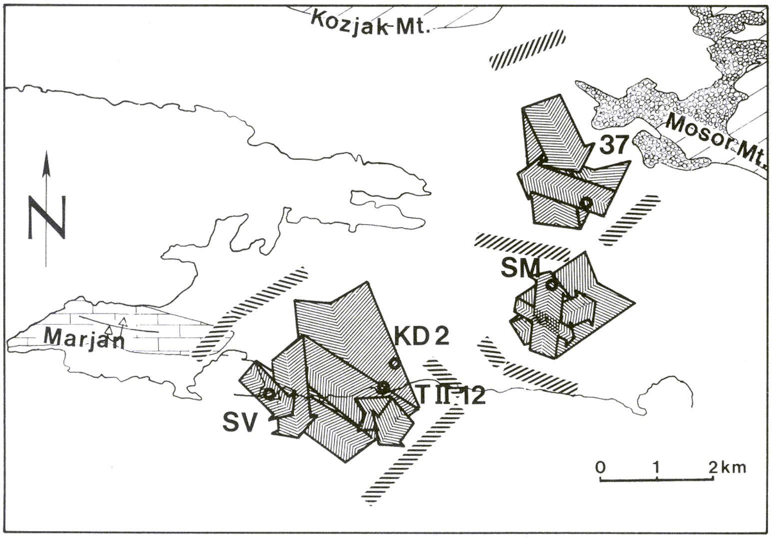

Fig. 7. The graphical reconstruction of flow reflections and approximate positions of the intrabasinal obstacles. The actual flow patterns were even more complicated.

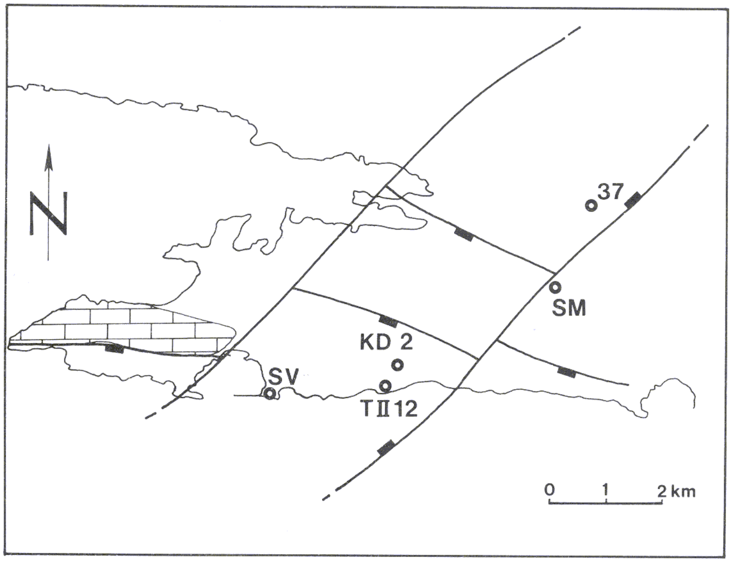

Fig. 8. Interpretative palaeogeological map. The area was dissected by SW–NE trending faults that cut listric normal faults, thus forming restricted sub-basins. The megabeds, however, are not restricted to a single sub-basin but also spread to a neighbouring one. The fault dividing the central and eastern areas is more prominent, because it is not possible to correlate megabeds across it.

CONCLUSIONS

The beds of reflected flows in the area studied provide some new insights into the palaeogeography of the Eocene Adriatic sedimentary basin.

(1) Thick lutites originated from the ponding effect of the large turbidity current tails and indicate a rather restricted depositional environment within the basin floor.

(2) Flow reversals indicate current head reflections from the obstacles within the basin, or from the opposite basin margin (slope). Repeated flow reversals and repeated sequences of sedimentary structures indicate rather small distances from these obstacles, thus indicating a complex bottom topography.

(3) Some reflected beds originated from flows of exceptional volume that were probably basin-wide and represent good markers, and they contain much of the possible palaeocurrent information in a single bed.

(4) Seiches seem to be more important in deep-sea basins than previously noted, as indicated by Van Andel & Komar (1969), Pantin & Leeder (1987), and Siegenthaler *et al.* (1987).

(5) A restricted basinal environment with effective ponding is a favourable place for turbidity current reflections and formation of seiches that produce symmetrical bedforms.

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REFERENCES

Benić, J. (1983) *Vapnenački nanoplankton i njegova primjena u biostratigrafiji krednih i paleogenskih naslaga Hrvatske.* PhD thesis, Faculty of Sciences Zagreb, 159 pp.

Blanchet, R. (1972) Sur un profil des Dinarides, de l'Adriatique (Split–Omiš, Dalmatie) au Bassin pannonique (Banja Luka-Doboj, Bosnie). *Bull. Soc. géol. Fr.*, **(7)**, **12**, 1010–1027.

Blanchet, R. (1975) De l'Adriatique au bassin pannonique. Essai d'un modèle de chaîne alpine. *Mém. Soc. géol. Fr. n. ser.*, **53/120**, 179 pp.

Bourrouilh, R. (1987) Evolutionary mass flow—Megaturbidites in an Interplate Basin: example of the North

Pyrenean Basin. In: *Megaturbidites* (Ed. by L. J. Doyle & R. Bourrouilh), *Geo-Mar. Lett.*, **7**, 69–81.

CHOROWICZ, J. (1977) Étude géologique des Dinarides le long de la structure transversale Split-Karlovac (Yougoslavie). *Soc. Géol. Nord.*, **1**, 3–331.

DŻUŁYŃSKI, S. & WALTON, K. (1965) *Sedimentary Structures of Flysch and Greywackes. Developments in Sedimentology*, No. 7, Elsevier, Amsterdam, 274 pp.

ELLIS, B.A. (1980) The lateral variations of structures within basinwide turbidites. *Abstr. First Eur. Reg. Meeting I.A.S. Bochum*, 115.

FREY, R.W. (1975) The realm of ichnology its strengths and limitations. In: *The Study of Trace Fossils* (Ed. by R. W. Frey), pp. 13–18. Springer-Verlag, Berlin.

GRUBIĆ, A. & KOMATINA, M. (1962/63) Osobine eocensko-oligocenskog fliša izmedju Splita i Makarske. *Sedimentologija*, **2/3**, 21–38.

HAMPTON, M.A. (1972) The role of subaqueous debris flow in generating turbidity currents. *J. sedim. Petrol.*, **42**, 775–793.

HISCOTT, R.N. & PICKERING, K.T. (1984) Reflected turbidity currents on an Ordovician basin floor, Canadian Appalachians. *Nature*, **311**, 143–145.

KERNER, F. (1903) Gliederung der Spalatiner Flyschformation. *Verh. geol. Reichsanst.*, **5**, 87–102.

KERNER, F. (1914) *Geologiche Spezialkarte der Österr.-Ungar. Monarchie* 1 : 75000, Sinj und Spalato, Vienna.

LABAUME, P., MUTTI, E. & SEGURET, M. (1987) Megaturbidites: a depositional model from the Eocene of the SW-Pyrenean Foreland Basin. In: *Megaturbidites* (Ed. by L. J. Doyle & R. Bourrouilh), *Geo-Mar. Lett.*, **7**, 91–101.

LARUE, D.K. & PROVINE, K.G. (1988) Vacillatory turbidites, Barbados. *Sediment. Geol.*, **57**, 211–219.

MAGAŠ, N. & MARINČIĆ, S. (1973) *Osnovna geološka karta SFRJ, 1: 100000, Tumač za listove Split i Primošten*, 5–47. Savezni geološki zavod, Beograd.

MARINČIĆ, S. (1981) Eocenski fliš jadranskog pojasa. *Geol. vjesnik*, **34**, 27–38.

MARJANAC, T. (1985) Composition and origin of the megabed containing huge clasts (Flysch formation, Middle Dalmatia, Yugoslavia). *Abstr. Sixth Eur. Reg. Meet. I.A.S. Lleida*, 270–273.

MARJANAC, T. (1986) *Sedimentacija dubokovodnih klastita paleogena sjevernog i istočnog zaledja Solina*. MSc thesis, University of Zagreb, 98 pp.

MARJANAC, T. (1987) Sedimentacija Kernerove "srednje fliške zone" (paleogen, okolica Splita). *Geol. vjesnik*, **40**, 177–194.

MARJANAC, T. (1988a) Reflected megabeds in Paleogene flysch of Middle Dalmatia (Yugoslavia). *Abstr. Ninth Eur. Reg. Meet. I.A.S. Leuven*, 136–137.

MARJANAC, T. (1988b) Paleotransporti u paleogenskom flišu okolice Splita i Solina. Zbornik radova 6. skupa sedimentologa Jugoslavije. *Geol. glasnik pos. izd.*, **6**, 101–107.

MARJANAC, T. (1989) Ponded megabeds and some characteristics of the Eocene Adriatic basin (Middle Dalmatia, Yugoslavia). *Mem. Soc. geol. It.*, **40**, 241–249.

PANTIN, H.M. & LEEDER, M.R. (1987) Reverse flow in turbidite currents: the role of internal solitons. *Sedimentology*, **34**, 1143–1155.

PAREA, G.C. & RICCI LUCCHI, F. (1975) Turbidite key beds as indicators of ancient deep-sea plains. 9. *Int. Congr. Sedim. Nice*, **1**, 235–242.

PICKERING, K.T. & HISCOTT, R.N. (1985) Contained (reflected) turbidity currents from the Middle Ordovician Cloridorme Formation, Quebec, Canada: an alternative to the antidune hypothesis. *Sedimentology*, **32**, 373–394.

RICCI LUCCHI, F. & VALMORI, E. (1980) Basin-wide turbidites in a Miocene over-supplied deep-sea plain: a geometrical analysis. *Sedimentology*, **27**, 241–270.

SIEGENTHALER, C., FINGER, W., KELTS, K. & WANG, S. (1987) Earthquake and seiche deposits in lake Lucerne, Switzerland. *Eclogae geol. Helv.*, **80**, 241–260.

SOUQUET, P., ESCHARD, R. & LODS, H. (1987) Facies sequences in large-volume debris- and turbidity-flow deposits from the Pyrenees (Cretaceous; France, Spain). In: *Megaturbidites* (Ed. by L. J. Doyle & R. Bourrouilh), *Geo-Mar. Lett.*, **7**, 83–90.

ŠIKIĆ, D. (1968) Istarsko Dalmatinska orogenetska faza i stratigrafija Eocena u Dinaridima. *I Kolokvij geol. Dinarida Ljubljana*, **1**, 135–142.

VAN ANDEL, T.H. & KOMAR, P.D. (1969) Ponded sediments of the Mid-Atlantic Ridge between 22° and 23° North latitude. *Bull. geol. Soc. Am.*, **80**, 1163–1190.

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