Distortion of the Salt-Cored Fold System and Its Effects upon Abyssal Plain Sedimentary Processes in the Cilicia-Adana Evaporitic Basin, the NE-Mediterranean*

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Abstract

The abyssal plain zones of the evaporitic environments generally provide very attractive structural targets as the associated salt-cored fold trains contain the first structures out of the basin where hydrocarbons are generated. The Cilicia-Adana basin contains upper Messinian evaporite interval which has undergone widespread halokinesis since Pliocene to a recent folding stage. Detailed interpretation of seismic reflection data was undertaken to gain insight into the formation, growth, and spatial distribution of salt-cored folds and their distortion by abyssal-plain sedimentary processes.

The deep-water abyssal plain of the basin underwent gravity-driven compression and contains a large variety of syn/post-sedimentary structures, including folds with different wavelengths-amplitudes and squeezed diapirs, displaying distorted-body styles. The salt-cored folding developed where updip extension was accommodated by downdip compression resulting from basinwide salt detachment, which is interpreted by varying modes of salt-sediment deformation, salt-diapir body distortion, and dating of their growth velocities.

Thickness of laterally migrated salt decreases southward, to the north Cyprus coast. The wavelength of diapirs also decreases southward, and estimated original salt thickness reaches maximum along the central basin graben, where the wavelength sharply increases. We postulate a strong positive relationship between salt thickness, diapir wavelength, and salt-body distortion. Diapirs seem to be spaced at a characteristic wavelength, not directly related to faults, and the wavelength varies smoothly through the area. However, there is a strong alignment of some mature diapirs, parallel to the W-E oblique-slip master fault trend, suggesting that their axis of elongation was controlled by faulting, with the main initial salt movement during early Pliocene, due to basin extension and buoyancy.

Introduction

The Cilicia–Adana salt-rich basin, in the NE corner of the Mediterranean, is an arcuate and elongate depocenter nestled between the Kyrenia-Misis Lineament in the SSE and the Taurus Mountains of south Turkey in the north and NW (Figure 1). In the west, the basin is separated from the Antalya Basin by the N-S-trending Anamur-Kormakiti zone (Anastasakis and Kelling, 1991**)**. Thus, it can be viewed as an intra-mountain basin, situated in a forearc setting, north of the Florence Rise and Cyprus Arc and forming the convergent boundary between the African and Aegean-Anatolian plates. The Cilicia-Adana basin is divided into an E-W-trending, deeper abyssal plain and a NE-SW-trending, shallower Adana delta platform margin in the NE. The Adana Basin in the NE is the onshore extension of the central Cilicia Basin (Figure 1). Various aspects of the Cilicia Basin have been investigated by Evans et al. (1978), Aksu et al. (1992a,b), and in a context of circum-Mediterranean basins by Robertson (1998), but its deeper ductile system and halokinetic structure were rather unknown until 2000. The dynamic evolution and structural development of this basin, as well as other basins are affected in many cases by salt tectonism and halokinetic regimes (Toker, 2003) (e.g., offshore west Africa, east Brazil, eastern Canada, Gulf of Mexico). Evaporitic sedimentary systems have been investigated in order to understand the complex sub-systems, such as mechanism of delta-overburden deformation above viscous creep of Messinian substratum of the Cilicia-Adana Basin (Toker et al., 2006). Salt tectonism and halokinesis have occurred on several passive continental margins; for instance, the Gulf of Mexico (Diegel et al., 1995), offshore margins of west Africa (Marton et al., 2000), and the Atlantic Canadian margin (Yassir and Bell, 1994). Sedimentary basins that have experienced salt tectonism are characterized by seaward thinning of sediment layers overlying the salt due to seaward progradation of sediments from adjacent onshore regions. The sediments are characterized by regions of landward extension beneath the shelf and seaward contraction (Tari et al., 2002). Studies that have contributed to the basis for this article and its conceptual framework include:

- Rheological and tectonic modeling of salt provinces by Weijermars et al. (1993).
- Numerical analysis of the effects of sedimentation and redistribution of surficial sediments on salt diapirism by Poliakov et al. (1993).
- Style and pattern of salt diapirs due to thin-skinned gravitational gliding, Campos and Santos basins, offshore Brazil by Demercian et al. (1993).
- Salt flow and diapirism related to extension at crustal scale by Nalpas and Brun (1993).
- Numerical modeling of salt diapirism and influence of the tectonic regime by Daudré and Cloeting (1993).

The abyssal plain of evaporitic environments (e.g., the Cilician abyssal plain) generally provide very attractive structural targets as associated salt-cored fold trains containing the first structures out of the basin where hydrocarbons are generated. Based on hydrocarbon maturation, trap formation, and timing, the abyssal plain of the Cilicia-Adana basin, within a Messinian evaporite setting of a subsiding syn-sedimentary graben, has created many dormant structures that differ from the post-sedimentary graben evaporitic setting with structural traps that tend to be continuously deforming and leading to the loss of hydrocarbons. In the basin, active regional tectonism and delta sedimentation recently produced contrasting salt-cored folds, which have varying and differing styles in the NE and in the W-E central abyssal plain--yet in the same evaporitic environment (Figures 2, 3, 4, and 5). The salt-cored fold modeling displays the sediment accumulation history of a basin unit in a particular time interval. Progressively active salt diapir and fold growth impact sediment dispersal paths upon abyssal plain, accommodation space for deposits, and subsequent potential hydrocarbon/salt migration routes and pathways, as well as the strain history (Richards et al., 2002). The present-day shape of deformed horizons by salt is well defined by seismic data (Figures 2, 3, 4, and 5). The shape change of depositional horizons through time, accompanying the salt-body growth, provides insight into the interplay of structural fold development, sediment accumulation, and hydrocarbon migration history.

The filling of accommodation space in a specific time interval shows the most likely channel paths of turbidite systems, areas of ponded turbidite deposition, and also the deformation of the sedimentary sections resulting from salt withdrawal and lateral movement. An excellent example in a complex salt-sediment body architecture in the Cilicia-Adana Basin (Figure 1) illustrates how the fold system is distorted by sedimentation and its effect on abyssal-plain sedimentary processes. Essentially, we intend to:

- Indicate distortion of the salt-cored fold system and its effects upon abyssal-plain sedimentary processes that might have a significant impact on sediment dispersal patterns and the resultant instability of the overburden system of the basin.

- Investigate the salt deformation process as well as salt mobilization/evacuation, salt emplacement mechanism, and the anomalous anatomy of salt-sediment body patterns along the abyssal plain.

Sediment distribution in the basin indicates two depositional patterns: Messinian evaporites and Plio-Quaternary sediments separated by an abrupt subaerial and strong unconformable erosional surface at the Miocene-Pliocene boundary, termed “Reflector M” by Ryan et al. (1966) and Woodside (1977) (Figures 2, 3A, and 5). We effectively used single channel-sparker seismic reflection data collected during the years of 1972-1977 by R/V Shackleton cruise governed by Graham Evans. Figure 1 shows a track chart of the geophysical survey with the major deltaic and structural provinces. Total length of seismic tracks positioned in the intershelf areas across the basin is approximately 750 km. Most of cruise lines were run perpendicular to the length of the basin (or N-S), while the other surveys were run subparallel or oblique to basin trend (Figure 1). Depth conversions from time sections on seismic data were made by using a sound velocity of 1500 m/s for the sea water and 2000 m/s for the Plio-Quaternary sediments. During the survey, the signal energy of the sparker source and the firing interval varied between 1 and 6 kJ and 1 to 4 ms, respectively, and the frequency range is 80 to 200 Hz.

Discussion and Results

Salt Mobilization, Salt Emplacement Mechanism, and Sedimentation

House and Pritchett (1994) suggested that the emplacement history of the salt, consisting of two phases (salt mobilization and salt deformation), clearly indicates the importance of how salt emplacement mechanisms developed in the Cilicia region, where Plio-Quaternary overloading caused salt mobilization/emplacement mechanisms. In the Cilician basin, much of Plio-Quaternary structural and depositional framework is controlled by the original primary emplacement and secondary remobilization of the salt body. The upward movement of the salt continues as long as it is sourced from a deeper salt body, which is presumed to be pre-Messinian or older (Miocene “main salt stocks”). The vertical and horizontal movement of salt has resulted in the widespread deformation of the basin plain (Figures 2, 3, 4, and 5). Regional extension occurring after diapir growth has utilized all of its available source salt. Collapse of the original salt body, which is considered to have been deeply sourced, resulted from salt evacuation and created the huge Plio-Quaternary depocenters above the deeper salt body (Figures 2, 3, and 4). If delta sedimentation is more rapid than can be accommodated by fault-fold compensation movement, sediments may “override” the fault-fold systems (Figures 3c and 5b).

The compensation faults, associated with high sedimentation rates (“overriding periods”) and upthrown in direction of sediment supply, often trap large volumes of sediments (Larberg, 1983). Accumulations in associated traps may be present in the huge Plio-Quaternary depocenter area and in basinwide salt fold-controlled minibasins (Figures 2, 3, 4, and 5). Some of these depocenters along the south margin of Turkey probably formed as tensional graben systems, due to salt withdrawal. Diapirism continues from east to west along the central abyssal plain, as diapir concentration decreases (Figures 4 and 5). The flowage of evaporites and diapirism has been directed toward the west, probably continuing due to massive sediment loading by the huge Plio-Quaternary depocenters and bathymetry (Figure 5). The Plio-Quaternary deposits document continued subsidence and filling of the deep basin throughout the Pliocene. During this time, salt formations reached the stage of diapir growth by the mechanical relationships between the sedimentary overburden and evaporitic behavior. The extension of sediments is implied by growth faulting as well as by salt flowage. It is likely, therefore, that the growth faulting is caused not only by the halokinesis, but also as a response to delta sediment loading and unstable shelf margin.

Salt-Cored Folding

The deep-water abyssal plain of the basin underwent gravity-driven compression as shown by a large variety of syn/post-sedimentary structures, including folds with different wavelengths-amplitudes and squeezed diapirs, displaying distorted body styles (Figures 2, 3, 4, and 5). The salt-cored folding driven by gravity is where updip extension is accommodated by downdip compression, because of basinwide salt detachment, interpreted by varying modes of salt-sediment deformation, salt-diapir body distortion, and timing of their growth velocities. Geometry and growth kinematics of salt-cored folds show that high-amplitude folds, from their growth histories, can potentially reveal important details of the physical behavior of salt and delta overburden. Because the initial characteristic wavelengths in Figures 3A and 4 are likely to be preserved, sedimentary beds are also easily traceable across the crests of the salt folds (Figures 2, 3, 4, and 5); thus original and/or localized salt thicknesses can be estimated in general terms.

Thickness of laterally migrated diapiric salt and the wavelength of diapirs decrease southwards, to the north Cyprus coast above reflector M (Figures 3A, a, and 4), and estimated original salt thickness reaches a maximum along the central basin graben setting where the wavelength sharply increases (Figures 3b and 4). We postulate a strong positive relationship between salt thickness, diapir wavelength, and body distortion (Figures 3, 4, and 5). Diapirs seem to be spaced at a characteristic wavelength, not directly related to faults, and the wavelength varies smoothly through the area. However, there is a strong alignment of some mature diapirs, paralleling the W-E oblique-slip master fault zone (Figures 2, 3A, and 3b), suggesting that their axis of elongation was controlled by faulting (Figure 5). The main initial salt movement was during early Pliocene, due to basin extension and subsequent buoyancy.

It is also recognized that there are two frontal boundary conditions in the formation of the body styles of the salt-cored folds: the wedge and the onlap pattern of delta sediment progradation over the salt, as *external buttress,* and the wedging of salt layer, as *internal buttress* (Figures 3A [to north], 3c, and 5b). External buttress, more generally characterized by newly formed compressional structures, favors the inversion of extensional structures and results in inaccurate interpretations of halokinetic evolutionary stages.

Diapiric salt waves migrate downslope during gravity gliding and by the frontal compression of salt-sediment layer wedging (Figures 3A [to north], 3c, and 5b). Seismic data indicate a better fit of external buttress with the Cilicia basin; of special interest is the sediment incorporation within the salt diapiric wave (Figures 3c and 5a, b). In thin-skinned tectonics, a sediment cover is sheared off from an underlying basement. In some cases, such detachments are located in salt horizons. During deformation, faults and narrow anticlinal folds can develop in the upper cover, showing that fold axis patterns are related to the position and shape of the faults.

During compression some of the synclines are progressively pinched and detached, and this gives birth to a typical delta-prograding wedge pattern and the effect of an external buttress (Figures 3a, c). Thus, we can identify some structural variations and details in the resulting geometry of salt-sediment fold system:

- Less efficient basinwide detachment with *syn-sedimentary salt* movement (syn-sedimentary folding).
- High efficient detachment with *post-sedimentary salt* movement (post-sedimentary folding). The detachment horizon reduces the transmission of stresses from the basement, and in such cases, the final deformation is very sensitive to local heterogeneities inside the overriding multilayer.
- The narrow and steep continental margins along the N-boundary of the basin tend to enhance the salt-cored folds at the toe of the slope toward the depositional limit of the salt (Figures 2, 3b, and 5).

- The existence of oblique-slip master fault at the mid-basin line corresponds to a sharp, fault-bounded termination of the original basinward depositional limit of the salt, resulting in the lack of a salt-cored fold belt farther west, regardless of the tectonic position of the salt (Figures 2 and 5).

In regard to the balance between extension and contraction for the basin, we infer that thin-skinned salt tectonism is gravitationally driven and independent of any basement tectonics. These considerations are also supported by Odonne and Costa, (1993). In their multilayer paraffin wax model, the fold axis patterns are very heterogeneous around a limited-length fault in the multilayer where the deviation of fold axes can reach 90° around the fault tips. They are quite homogeneous around an unlimited-length fault, irrespective of its location. An unlimited-length fault mainly induces only a slight deviation of the fold axes due to strike-slip movement.

Distortion of the Salt-Cored Folding

The progressive development and evolution of the Cilician salt-cored fold system are the function of:

- Primary depositional geometry and basin tectonics (Figure 5).
- Initial thickness of sedimentation (pre-deformation phase by salt) (Figure 5).
- Synchronized sediment rate with upward salt deformation (syn-deformation phase by salt) (Figure 5b).
- Mother salt stock and feed-back rates. In relation with these, time relationships between fold growth and its distortion by sedimentation can be taken into account as the following phases:
    - *Synchronization* involving the two critical parameters: (i) high sedimentation rate or great supply of sediments and (ii) great rate of diapir growth or great supply of the salt stock. These parameters confirm trapped sedimentary patterns (confinement/entrapment mechanism) in the folded structures. There exists an equilibrium not only between the main salt stock and sediment accumulation rate but also between salt withdrawal compensation (SWC) and sediment accommodation rate (CSL--compensatory sediment loading). Synchronous relationship is mostly due to broadly widening salt-stock chamber in terms of the paleo-topographic structure (M-reflector) supported by a gradient of rapid graben subsidence in the NE abyssal plain (Figure 5). Note in Figure 5b that the diapirs (on the right) are out of the sediment deformation front and undistorted piercement diapirs. They were uplifted recently, after the development of distorted diapirs, which were first to experience the deformation and became asymmetric anticlinal features (Figure 5b). Thus, they represent “synchronization” in the same province, while the others are diachronous (Figures 5a, c). Figures 3c and 5b illustrate synchronous diapir growth, with sediment deformation, indicating syn-diapir infill geometry and wedge-shaped sedimentary packages between salt swells.
    - *Diachronization* involving two critical parameters: (**i**) high sedimentation rate or great supply of sediments and (**ii**) low rate of the diapir growth or low supply of salt stock. Great supply of sediment cannot trigger synchronous diapir growth or high concentration of diapirism, due to less salt stock. This is controlled by the narrowed chamber of the salt stock within a paleo-topographic depression (reflector M), which is probably due to the oblique-slip master fault zone, with an expected termination and loss of evaporites (Figure 5). Yet, there are several linear and elongate groups of diapirs that migrated westward in a shape similar to that of a paleo-channel system (M-reflector) (Figures 2, 3b, and 5). In this case, the rate of diapir growth and sediment accumulation represent “diachronization,” which is reflected by undistorted crestal patterns and symmetric anticlinal forms (Figures 2, 3a, b, and 5a, c). The illustrated diachronous diapir growth, with regularly ponded, or trapped, sedimentary infill patterns, was controlled by buoyancy and especially differential sediment loading.

Note that in Figure 5 the seismic profiles are the areal representatives of the distorted/undistorted folding styles and their locations in the basin paleo-bathymetry at Reflector M. Consequently, salt-cored folds have formed in recent times and shaped the present-day basin plain. Seismic profiles show that the relief observed along the Cilicia basin plain arises mainly from salt-cored fold belts and strongly controls sediment transport and dispersal patterns to the south - southwest - west. In terms of the formation mechanism of the anticlinal and synclinal features, it is presumed that a compressional plate margin through Cyprus would produce N-S compression in the area, giving E-W folds, but this assumption does not explain the salt-related doming or folding in the basin. It was discussed by Evans et al. (1978) that the compressional effect is not thought to be efficient, except for the flanks of the north Cyprus margin (strongly draped sedimentary patterns ([Figure 3A, 3a] on the Kyrenian flank). The best explanation for the origin of the salt diapirs and related fold belts in the basin is most probably "*extensive sedimentary diapirism*", along with Plio-Quaternary delta overburden, which is more than 1.5 km thick. It is concluded that the most important mechanisms in the formation and distortion of the fold belts are the salt withdrawal compensation features both locally and regionally, dynamics from uneven, asymmetric delta overburden, and rapid, differential graben subsidence. All these have recently played a critical role and commonly contributed to the extensive interaction of salt-sedimentary diapirism and folding. The salt-diapir-rich, unstable and relatively young Cilicia-Adana sedimentary basin system is a prominent example of gravitational potential energy. Salt-cored folding and its anomalous architectures are expressions of the gravitational potential difference becoming lower-- to density equilibrium (or neutral buoyancy - "*equipotential*) over the basin plain.

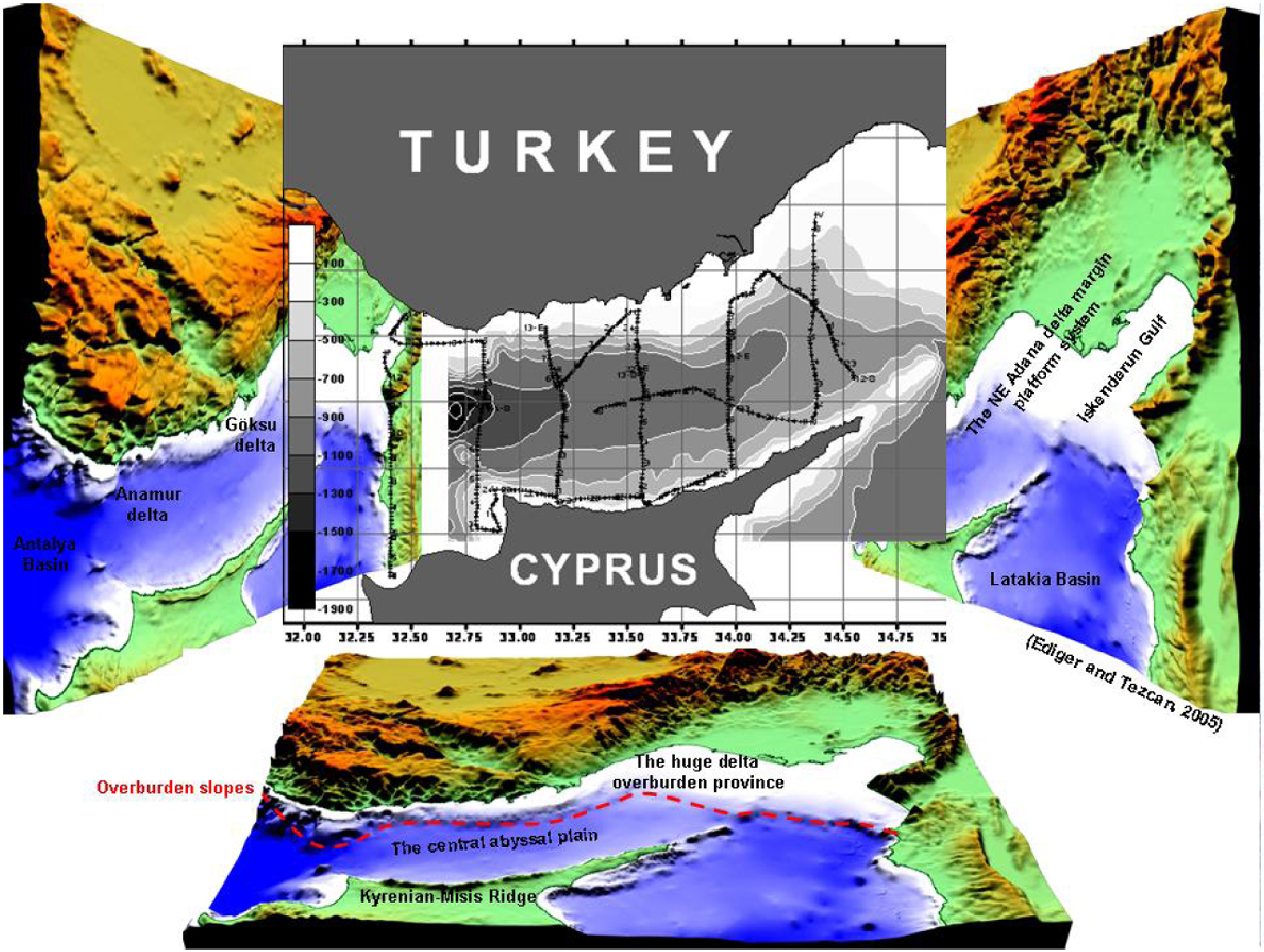

Figure 1. Seismic track lines, bathymetry (m) of the study area and its recently updated bathymetry in different perspective views by Ediger and Tezcan (2005). Note the major overburden slopes (red dashed line) of the huge deltaic provinces.

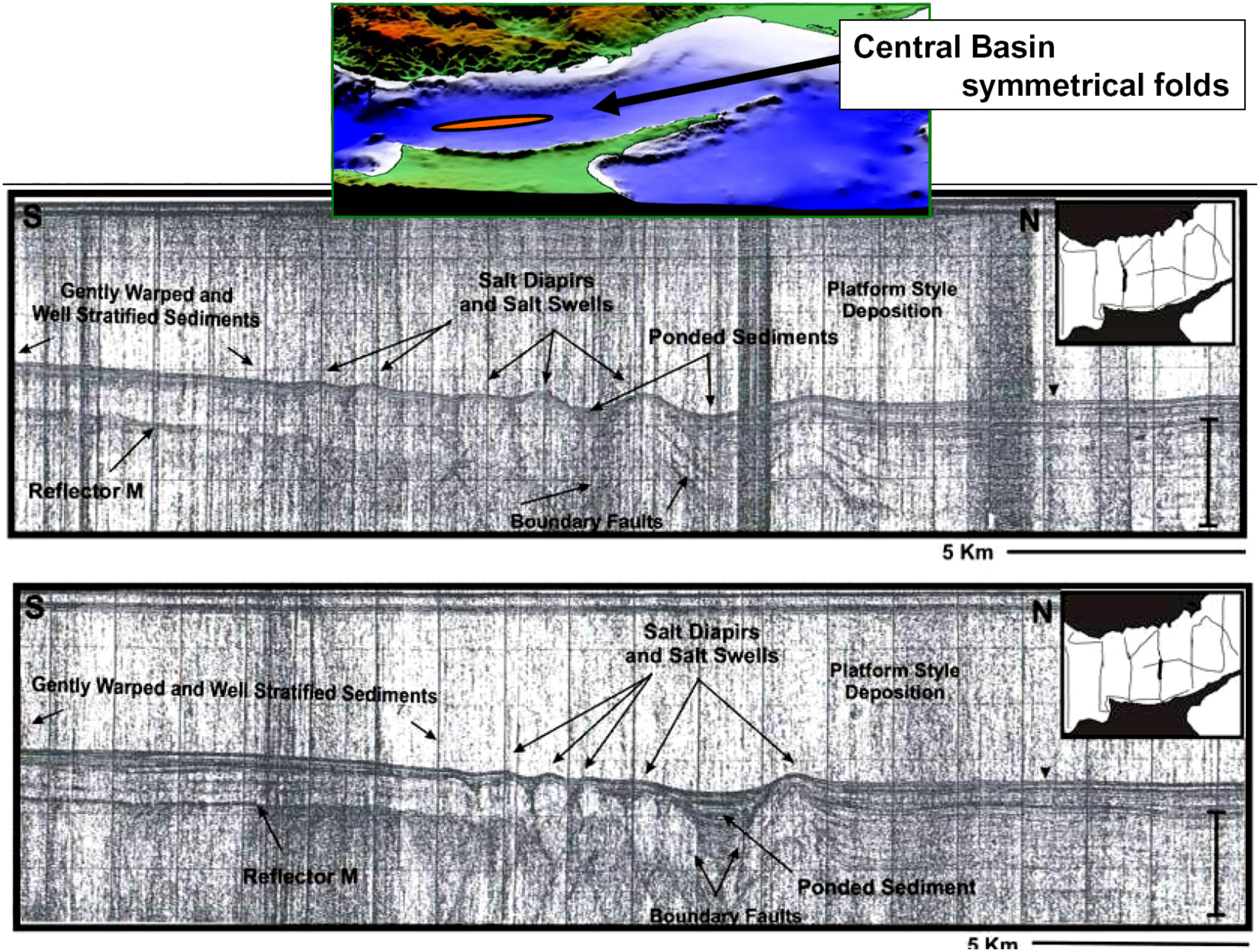

Figure 2. Seismic profiles, the central abyssal plain of the basin. In both profiles, the salt-cored folding subjected to internal bedding and diffractions. Solid vertical bar represents the scales of the profiles (TWTT: 800 ms; bathymetry: 600 m; sediment thickness: 800 m).

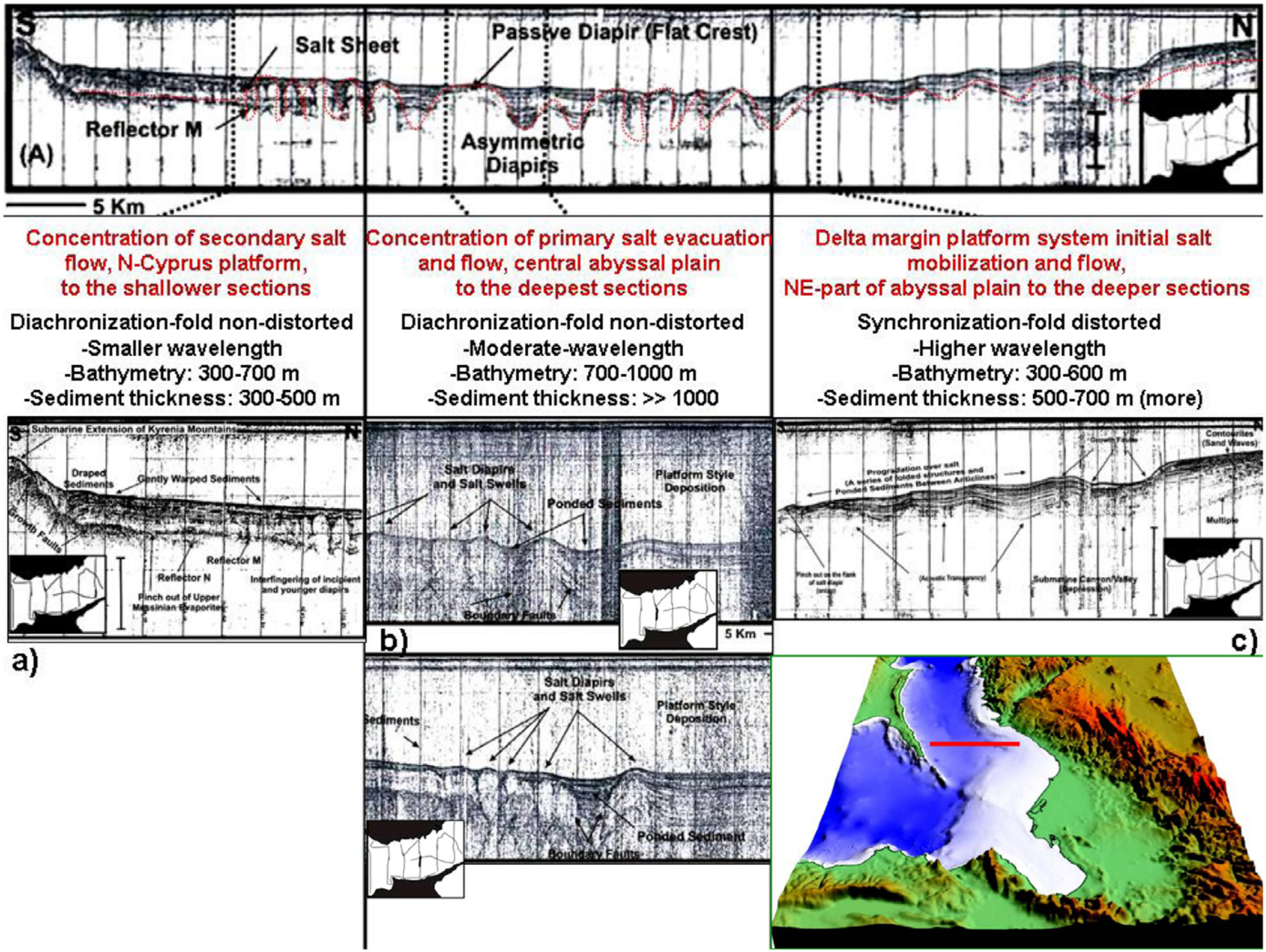

Figure 3. Seismic profile (A) with red dashed line illustrates the geometry of an inter-marginal salt withdrawal syncline (basin) (south Turkey to north Cyprus) and contrasting fold frequencies of salt-sediment body styles. Inter-marginal salt-sediment dynamics and related water depth, sediment thickness, wavelengths, and distortional styles are also indicated in a, b, and c profiles. Scale is the same in Figure 2).

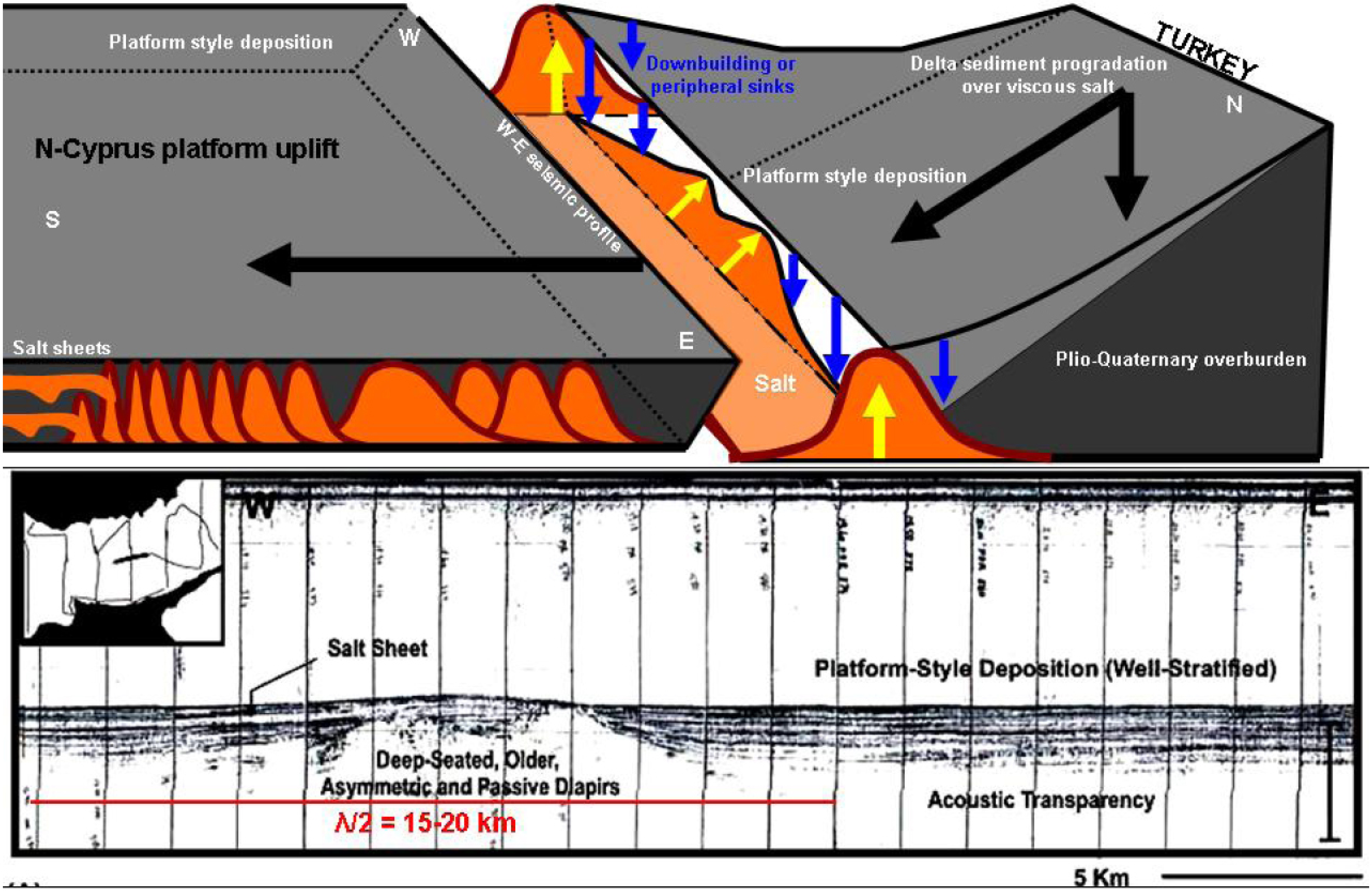

Figure 4. W-E seismic profile, central abyssal plain (lower), shows the main salt flowage to the west. This profile illustrates the greatest half-wavelength of passive diapir (15-20 km). Water depth: 900-100 m; Plio-Quaternary sediments: greater than 1000 m thick. Simplified 3D-basin model (upper) of the salt-sediment-fold dynamics (e.g., doming, downbuilding, diapir migration to the south with salt-sheet flows) indicated in profile. Scale is the same in Figure 2.

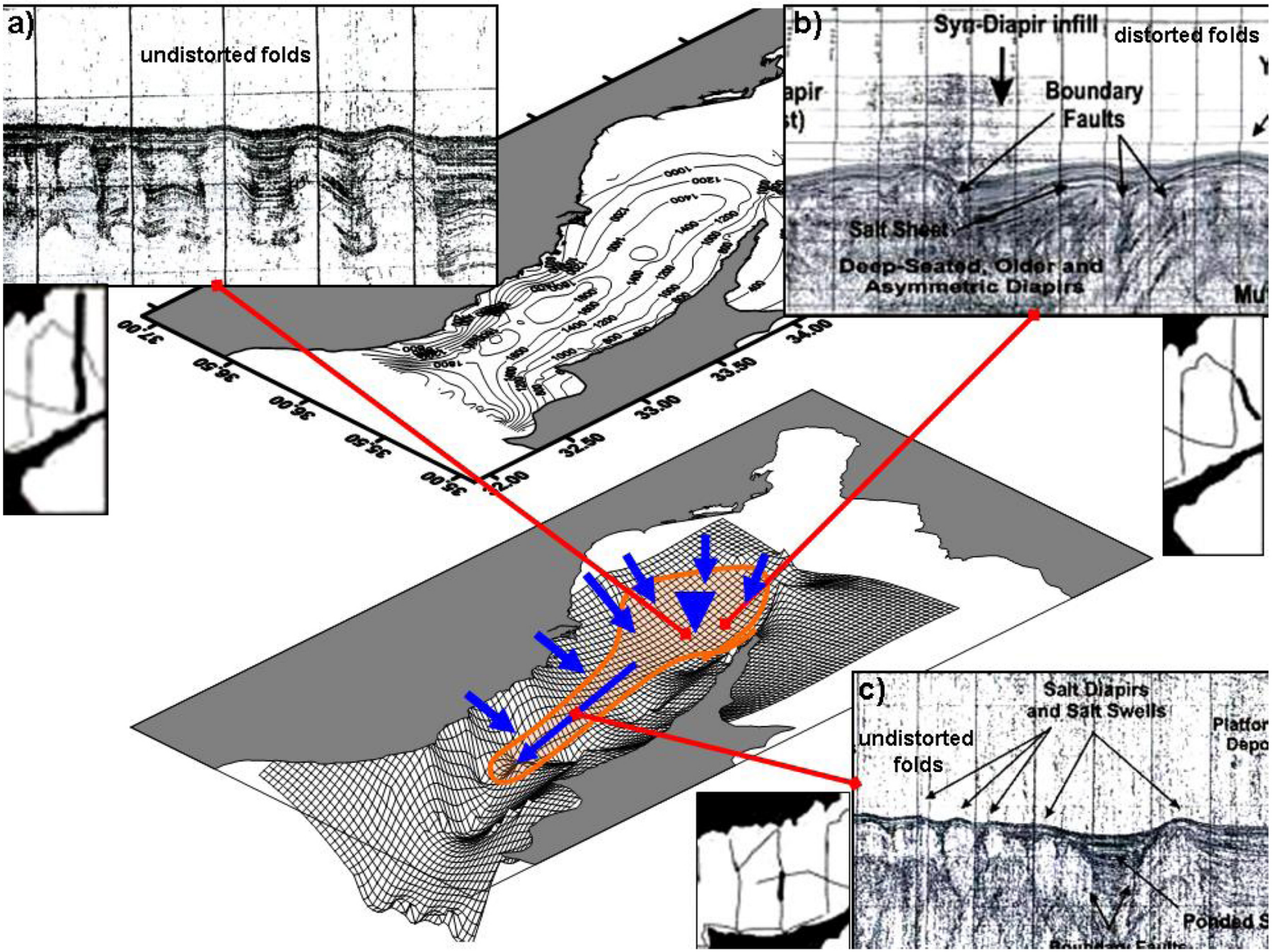

Figure 5. 3D-view of late Messinian basin geometry/paleo-bathymetry, based on reflector M; contour map of it shown between a) and b). Note the curvilinear Cilician-Adana, transtensional graben system ("Cilician Trough"), in which the Plio-Quaternary depositional environment has controlled salt-sediment body styles and fold architecture. Red lines show data and their locations. Blue arrows: major trends of salt migration-sediment gravity flow into abyssal plain. Orange polygon: basinal distribution of salt diapirism and the salt-cored fold system province.

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