New insights on Messinian evaporites based on field and seismic interpretations in the Neogene Antalya Basin, SW Turkey

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Abstract: In situ/primary Messinian upper evaporite is absent in the onland (onshore) sections of the Aksu and Manavgat subbasins (Antalya Basin), where gypsum blocks, gypsum conglomerate, and laminated gypsum beds mixed with siliciclastic materials are collectively present in the uppermost Messinian—lowermost Pliocene succession. The metric-size resedimented evaporite blocks, mainly derived from selenite-dominated marginal/upper evaporite, were deposited time-equivalent to the lower-middle parts of the reeval Gebiz limestone in the Aksu subbasin. Resedimented bedded evaporites were accumulated after siliciclastic-dominated (fluvio-deltaic) sedimentation of the Taşlık Formation in the Manavgat subbasin (nearby Antalya city). Some bedded/resedimented gypsums were defined within the Gebiz limestone and the Esikköy Formation, as observed in the logs of the Aksu-1, Manavgat-1, and Manavgat-2 wells. Effects of the Messinian salinity crisis are seen on the seismic boundary of the Messinian erosional surface in the Aksu subbasin resting directly on the Karpuzçay Formation and in the lower and middle parts of the fluvio-deltaic Esikköy Formation and reefal Gebiz limestone. As for the Manavgat subbasin, Manavgat-1 and -2 well logs indicate the existence of bedded/resedimented evaporites in the Taşlık and Esikköy Formations, which is supported by the seismic sections. Additionally, onshore and offshore seismic sections indicate that the upper evaporite layer could be traceable both in onshore and offshore areas. The relationship between evaporite and nonevaporite units is explained by the Aksu phase, which caused compressional deformation leading to significant uplift in the region around the Gebiz High. This uplift is also involved in relative sea-level drop, which resulted in alternating deposition between siliciclastic (Esikköy and Taşlık Formations), resedimented-bedded gypsum, and transgressive shallow marine reefal Gebiz limestone.

Key words: Miocene-Pliocene, Aksu-Manavgat subbasins, evaporite, seismic, well logs

1. Introduction
The Antalya Neogene Basin in southwestern Turkey predominantly includes Miocene and Pliocene deposits that in-filled a marine and partly inverted extensional basin (Akay and Uysal, 1985; Flecker et al., 1995; Yagmurlu et al., 1996; Glover and Robertson, 1998a, 1998b; Collins and Robertson, 1998). These sediments unconformably overlie the Antalya and Alanya nappes that were thrust over the Mesozoic carbonate platform during the Late Cretaceous (Bizon et al., 1974; Poisson et al., 1983; Akay and Uysal, 1985; Şenel et al., 1992; Özgüner and Varol, 2009). The Miocene succession is overlain by Plio-Pleistocene fluvio-deltaic deposits within a structural extensional context (Glover and Robertson, 1998a, 1998b; Kosun, 2012). The Lower Miocene is represented by an overall transgressive sequence that comprises, from base to top, alluvial fan and fan-delta conglomerates (Tepekli Formation), reefal limestone (Oymapınar Formation), and basinal shale deposits (Geceleme Formation) (Flecker et al., 1995, 1998). The Middle and Upper Miocene comprise fine-grained deposits and thin-bedded turbidites from the Karpuzçay Formation (Akay and Uysal, 1985) that locally interfinger with coarse clastic units of the Aksu Formation (Akay and Uysal, 1985; Glover and Robertson, 1998a, 1998b). Above the bioclastic and marly succession of the Karpuzçay Formation, the rapid shallowing observed at the transition to the overlying Taşlık Formation is taken as evidence of forced regression in the basin around the Gebiz High (Akay and Uysal, 1985), which includes terrigenous conglomerate-siltstone, marine conglomerate-sandstone, and reef limestone lenses, deposited in a context of sea-level changes represented by short intervals of transgressive-regressive episodes interrupted by the Aksu phase.

The Antalya Basin was classified as a foreland basin related to southeastward emplacement of the Lycian...
nappes, altered by extensional or transtensional faulting (Flecker et al., 1995). The present configuration of the basin contains three subbasins called Aksu (AS), Köprüçay (KS), and Manavgat (MS). They are divided by the north-south-trending Kirkkavak fault and the westward-verging Aksu thrust (Çiner et al., 2008). Basinal morphology was constrained by setting positions of the subbasins within the Isparta angle. The eastern margin of the basin was affected by compressional deformation in the Early and Middle Miocene associated with final emplacement of the Lycian nappes and tightening of the Isparta angle (Kissel et al., 1993). This compressional deformation is considered to have been pursued by phases of crustal extension or transtension in the Burdigalian and Late Serravallian-Early Messinian to form three subbasins (Aksu, Köprüçay, and Manavgat) (Çiner et al., 2008). Reverse faulting took place during the Late Miocene, related to a phase of Late Miocene compression and/or transpression (Aksu phase) associated with regional nappe emplacement (Lycian nappes) and/or collision of Arabia and Anatolia further east in the Zagros region (Glover and Robertson, 1998b). According to Flecker et al. (1998), the large-scale recumbent folding and high-angle thrust faulting of the area occurred due to the Late Miocene to Pliocene compressional Aksu phase.

The Late Miocene to Earliest Pliocene compressional episode (Aksu phase) resulted in postdepositional deformation of the Miocene succession in the Gebiz High in the eastern part of the Aksu subbasin and E-W compressional stress caused distributed folding and thrusting during the Late Miocene Aksu phase (Glover and Robertson, 1998b; Üner et al., 2011, 2018). As a result of this folding and thrusting, the Aksu and Köprüçay subbasins were separated by the Gebiz High (Flecker et al., 1998; Deynoux et al., 2005).

The Antalya Basin studied here is one of the important Messinian evaporite basins in the eastern Mediterranean that is partly exposed onshore (Figure 1). Three parts of the Antalya Basin will be dealt with within the scope of this study: offshore, Manavgat, and Aksu subbasins. Although Messinian evaporites in Antalya Bay have been clearly detected in marine seismic sections right underneath and throughout the Messinian unconformity, they have been considered to be absent in onshore sections, or only observed as restricted outcrops of reseddimented evaporites in the eastern part of the basin. This study focuses on the location of the Messinian evaporite and related sedimentary units deposited before, during, and after the evaporite stage from outcrop observations, seismic sections, and well data.

2. Materials and methods
A total of 67 samples were studied within the scope of this study. Forty-five of these samples were derived from two outcrops, one in the Aksu subbasin (700 m thick) and the other in the Manavgat subbasin (400 m thick); the remaining 22 represent point samples.

Facies associations are defined on the basis of field sedimentological and paleontological observations, complemented by laboratory analysis on sedimentary petrography and micropaleontology (benthic/pelagic foraminifers, nannoplankton, and palynomorphs). A total of 15,000 km 2D seismic sections, both onshore and offshore, were used in this study.

The recorded data of offshore seismics consisted of an air gun source with 64 guns, 6 m streamer and source depths, 3600 m streamer length, and 30 m distance from shots. The distance between recordings was set as 15 m. The processing sequence included resampling, trace editing, spherical divergence filter correction, and predictive deconvolution. Applications of provisional velocity analysis, Kirchhoff dip moveout process, final velocity analysis, normal moveout correction, stack and F-X domain migration, and trace equalization processing of offshore seismic sections were completed.

Dynamite as a source with 240 channels, 5 s record length, 25 m receiver interval, and 50 m source interval was used for onshore seismic sections’ recording. Processing of onshore seismic reflection data consisted of resampling, trace editing, spherical divergence correction, exponential gain correction, spiking deconvolution, filter (8–12–50–75 Hz bandpass), automatic gain control, field static correction, velocity analysis, automatic residual statics, second velocity analysis, normal moveout correction, mute, second automatic residual statics, and stack (nominal fold 60). The processing steps were concluded by applying migration. All seismic sections and their interpretations are presented in time domain.

Well logs (sonic [DT], gamma ray [GR], and caliper [CALI] logs), post well sections, and paleontology reports of Manavgat-1 (2287 m), Manavgat-2 (2247 m), and Aksu-1 (2658 m) were used for seismic interpretation, correlation, and lithology definition.

3. Stratigraphy
Some of the main stratigraphic features and sequence boundaries seen in the Antalya Basin can be recognized in other Neogene basins in the Mediterranean region (Weijermars et al., 1985; Boeger and Dermitzakis, 1987; Dabrio, 1990; Steininger et al., 1990; Dalla et al., 1992; Lonergan and Schreiber, 1993; Yetis et al., 1995; Esteban, 1996; Kosun et al., 2009). This suggests that large-scale allochthonous processes, such as eustasy and regional tectonic events, acted synchronously to some extent and left similar stratigraphic imprints in a number of associated basins. The most remarkable is perhaps the Messinian salinity crisis (MSC; e.g., Hsü et al., 1977; Mascle and Mascl, 2019 and references therein), which in the Latest Miocene forced a major regression upon all basins con-
nected to the Mediterranean Sea. Messinian evaporites are known from offshore parts of the Antalya Basin (Taviani and Rossi, 1989) where the sea-level drop associated with the salinity crisis is marked by shallowing and regional regression caused by the Aksu phase, which is evidenced by resedimented-bedded gypsum and gypsum blocks, and fluvial incisions in the onshore part of the Antalya Basin (Dündar and Varol, 2014). As a result of this, the Taşlık Formation in the Manavgat subbasin (Figure 2) is overlain by resedimented-bedded gypsum and gypsum blocks starting with gypsum conglomerate containing various amounts (10%–30%) of siliciclastic grains. It was locally deposited during the Latest Messinian time (Dündar and Varol, 2014). Additionally, this regression involved the deposition of the Messinian Eskiköy Formation and consists of conglomerate-sandstone, starting with the development of fan deltas, overlapped by transgressive shallow marine reefal carbonate sediments (Gebiz limestone) (Akay and Uysal, 1985; Karabiyıkoglu et al., 2005; Dündar and Varol, 2014).

The fluvial deposits of the Eskiköy Formation, which have been interpreted as an axial submarine fan system, are bordered by coral reefs (Gebiz limestone). Gypsum blocks were deposited in the lower-middle parts of the Gebiz limestone in the Aksu subbasin (Figure 2). The claystone and sandstone of the Y enimahalle Formation and the sandstones with volcanic tuffs and conglomerates of the Alakilise Formation, deposited during the Early and Late Pliocene, make up the rock succession of this basin (Akay and Uysal, 1985).

Miocene and Pliocene sedimentation in the Antalya Basin has been clearly observed in and around the Aksu River and Manavgat, and throughout Antalya Bay (Figure 2). This picture is complicated by the postulated Aksu phase of compressional deformation, which in Late Tortonian to Early Messinian time is believed to have caused significant uplift in the region around the Gebiz High, giving rise to a drop in relative sea level (Figure 2).

3.1. Evaporite stratigraphy

The onshore stratigraphic position of the Messinian evaporites shows a different setting from the Aksu to Manavgat subbasins.

Field evidence in the Aksu subbasin indicates that selenitic gypsum and/or blocks are probably time-equivalent to the lower-middle parts of the Gebiz limestone, represented by small patchy reefs and local

Figure 1. Tectonic setting of Antalya and adjacent evaporite-bearing eastern Mediterranean basins. EAFZ: East Anatolian fault zone; DSZF: Dead Sea fault zone; M-AL: Misis-Andırın lineament; FBFZ: Fethiye-Burdur fault zone. 1) Antalya Basin (this study). 2) and 3) Polemi, Pissouri, Maroni, and Mesoaria Basins of Cyprus (e.g., Robertson et al., 1995, Manzi et al., 2016). 4) IODP leg 161 (Iaccarino et al., 1999a, 1999b). 5) Adana Basin (Darbas and Nazik, 2010; Ilgar et al., 2013). 6) İskenderun Basin (Albora et al., 2006; Tekin et al., 2010). 7) Hatay Graben (Boulton et al., 2006, 2007a, 2007b, Tekin et al., 2010). 8) Latakia Graben (Hardenberg and Robertson, 2007, 2013, 2016) (modified from Boulton, 2016).
rhodolites interfingering with alluvial fans (Eskiköy Formation). However, the Gebiz reefal carbonates cannot be identified in the corresponding offshore 2D seismic sections. The evaporites can be easily detected in both onshore and offshore seismic sections (see Section 4 for details). Onshore gypsum has been discovered in two limited outcrop locations.

The first outcrop is represented by the blocks of 2–5 m of selenitic gypsum in the vicinity of the village of Gebiz, where Gebiz limestone and gypsum are observed near the water supply channel (Poisson et al., 2011; Dündar and Varol, 2014) (Figure 3A). In this location, Gebiz limestone and gypsum blocks are conformably overlain by the mudstone of the Y enimahalle Formation. The transition zone includes Late Miocene-Pliocene-aged microfossils (Table 1A). The formation is mainly represented by a prograding deltaic unit characterized by prodelta mud, pillows indicating loading deformation, and cross-bedded delta plain sands (Figure 3B).

The second evaporite outcrop found to the northeast of Manavgat (nearly 10 km away from the city center, along Alaraçay in the Çadırlitepe realm) makes up a succession of gypsum 40 m thick topped by shallow marine deltaic sandstones-conglomerates and fluvial parts of the Taşlık Formation (Figure 4A). The basal part of the evaporites contains gypsum conglomerates with siliciclastic grains (10%–30%) and resedimented-bedded gypsum beds alternating with blocks of laminated gypsum and selenitic gypsum (Figure 4B). The chaotic gypsum deposit is mixed with coal-bearing mudstones in the uppermost part of the Taşlık Formation (Figure 4C). The relationship between the mudstone of Taşlık Formation and gypsum cannot be clearly discriminated in the field due to the unseen boundary between different lithological units (Figure 4D). However, palaeontological data obtained from the overlying thin coal-bearing mudstone, mostly coal and plant debris, yield Late Miocene-Early Pliocene fossils (probably Latest Messinian) (Table 1B).

4. Seismic description and interpretation
The effects of the MSC in Antalya Bay can be clearly recognized from reflection seismic data in the form of deeply reshaped basin margins of the Mediterranean basin, together with the development of evaporites in the deeper basin.

Three distinct evaporite units have been described as “lower evaporites” (carbonates and evaporitic sediments), “salt” (halite and anhydrite; mobile layer), and “upper evaporites” (marls and gypsum) (Ryan et al., 1973; Aksu et al., 2018). However, İşler et al. (2005), Aksu et al. (2009, 2018), Hall et al. (2005, 2009, 2014), Castellanos et al. (2009), Güneş et al. (2018a, 2018b, 2018c), and Lymer et al. (2018a, 2018b) have shown mainly three prominent seismic stratigraphic units: Pliocene-Quaternary (unit 1), Messinian (unit 2), and Pre-Messinian (unit 3), identified by using seismic reflection and well data in the area. Micallef (2018) identified the units as Plio-Quaternary fine-grained marine sediments (unit 1) and Messinian evaporites (unit 3), which are locally separated by a distinct body with chaotic to transparent seismic characteristics.
(unit 2). Micallef (2018) also identified several surfaces (also observed by different researchers) that are associated with MSC; e.g., MES: Messinian erosional surface/marginal erosional surface, BES: bottom surface/bottom erosional surface (or N-reflector), and TS/TES: top surface/top erosional surface (or M-reflector) (Lofi et al., 2011a, 2011b; Roveri et al., 2014a, 2014b; Cameselle and Urgeles, 2017; Aksu et al., 2018; Lymer et al., 2018a, 2018b; Güneş et al., 2018a, 2018b, 2018c).

According to Dunbar and Rodgers (1957), unconformities are surfaces of erosion and/or nondeposition that constitute time-gaps in the geological record. Unconformities create reflections as they separate beds with different physical properties (e.g., lithologies, density, porosity, permeability) and therefore give different acoustic impedance characteristics. The age classifications of the strata below the unconformity are older, while the beds overlying the surface are younger (e.g., Pomerol et al., 2005). Additionally, unconformity-bounded depositional sequences are typically characterized by stratal onlaps (Christie-Blick, 1991).

The MES in this study is represented by a significant erosional unconformity described as the MES and M reflector (Figure 5) in agreement with Maillard et al. (2006).
and Castellanos et al. (2009). This MES is characterized onshore by the presence of deep and narrow incisions and/or canyons, as reported by Chumakov (1973), Clauzon (1978), and Aksu et al. (2018). This study reveals the presence in the Aksu subbasin of the Pliocene reflector, the MES, and three west-vergent thrust faults crossed within the Aksu-1 onshore well (Figure 5A).

The Pliocene-Quaternary unit 1 corresponds to the Belks and Yenimahalle Formations that have relatively strong reflectors and good lateral continuity of reflective sediment package, distinguished by well logs, foraminifer, nannoplankton, and palynology results (Tables 1A and 1B). Unit 2 is described as an Upper Messinian-Lower Pliocene compromise with the Eskiköy Formation and Gebiz limestone, which has a lateral transition in the Aksu subbasin in consideration of the Taşlık Formation in the Manavgat subbasin. Unit 2 is characterized by bright, strong, and traceably continuous reflections related to the characteristic acoustic impedance at the top of the unit (Figure 5A) that correlates with the Messinian evaporite and the siliciclastic successions associated with the MSC (Aksu et al., 2018).

The seismic interpretation has been tied to the Manavgat-1, Manavgat-2, and Aksu-1 onshore wells. The Aksu-1 well is located 20 km NE of Antalya on a structural high related to the Aksu tectonic phase. The Manavgat-1 and Manavgat-2 wells are located immediately SW of Manavgat (Figure 6).

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**Table 1. A) Fossil content of Gebiz limestone – Yenimahalle Formation (Aksu subbasin).**

<table>
<thead>
<tr>
<th>Foraminifers</th>
<th>Nannofossils</th>
<th>Palynomorphs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neogloboquadrina datertrei datertrei</td>
<td>Coccolithus pelagicus</td>
<td>Artemisiapollenites sp.</td>
</tr>
<tr>
<td>Orbulina universa</td>
<td>Discoaster surculus</td>
<td>Compositae tubuliflorae-type</td>
</tr>
<tr>
<td>Orbulina suturalis</td>
<td>Discoaster variabilis</td>
<td>Compositae liguliflorae-type</td>
</tr>
<tr>
<td>Globigerinoides bolli</td>
<td>Helicosphaera kamptneri</td>
<td>Laevigatosporites haartdii</td>
</tr>
<tr>
<td>Globigerinoides obliquus</td>
<td>Sphenolithus heteromorphus</td>
<td>Periporopollenites multipuratus,</td>
</tr>
<tr>
<td>Globigerinoides sacculifer</td>
<td>Discoaster spp.</td>
<td>Periporopollenites stigmus</td>
</tr>
<tr>
<td>Globigerinoides trilobus</td>
<td>Reticulofenestra spp.</td>
<td>Verrucatosporites favus</td>
</tr>
<tr>
<td>Globigerinoides extremus</td>
<td></td>
<td>Pityosporites spp.</td>
</tr>
<tr>
<td>Globigerina sp.</td>
<td></td>
<td>Saxosporis sp.</td>
</tr>
<tr>
<td>Globorotalia sp.</td>
<td></td>
<td>Achomosphaera andalousiensis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lingulodinium machacrophorum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Homotryblium plectilum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hystrichokolpoma rigaudiae</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cleistosphaeridium sp.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cordosphaeridium sp.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impagidinium sp.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spiniferites sp.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Botryococcus braunii</td>
</tr>
</tbody>
</table>

**Table 1. B) Fossil content of Taşlık Formation (Çadrlitepe section, Manavgat subbasin).**

<table>
<thead>
<tr>
<th>Foraminifers</th>
<th>Nannofossils</th>
<th>Palynomorphs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Globigerinoides immaturus</td>
<td>Amaurolithus primus</td>
<td>Artemisiapollenites sp.</td>
</tr>
<tr>
<td>Globigerinoides obliquus</td>
<td>Amaurolithus delicatus</td>
<td>Compositae tubuliflorae-type</td>
</tr>
<tr>
<td>Globigerinoides quadrilobatus</td>
<td>Calcitiscus macintyre</td>
<td>Compositae liguliflorae-type</td>
</tr>
<tr>
<td>Globigerinoides sacculifer</td>
<td>Coccolithus pelagicus</td>
<td>Hystrichokolpoma rigaudiae</td>
</tr>
<tr>
<td>Globigerinoides trilobus</td>
<td>Helicosphaera kamptneri</td>
<td>Lingulodinium machacrophorum</td>
</tr>
<tr>
<td>Globigerina sp.</td>
<td>Reticulofenestra pseudoambilica</td>
<td>Operculodinium centrocarpum</td>
</tr>
<tr>
<td>Globigerina sp.</td>
<td>Sphenolithus abies</td>
<td>Spiniferites ramosus granosus</td>
</tr>
<tr>
<td>Globorotalia sp.</td>
<td>Sphenolithus heteromorphus</td>
<td>Polysphaeridium sp.</td>
</tr>
<tr>
<td>Globoturborotalita sp.</td>
<td>Sphenolithus moriformis</td>
<td></td>
</tr>
<tr>
<td>Orbulina sp.</td>
<td>Sphenolithus moriformis</td>
<td></td>
</tr>
<tr>
<td>Scitula</td>
<td>Discoaster spp.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reticulofenestra spp.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sphenolithus spp.</td>
<td></td>
</tr>
</tbody>
</table>
First, DT logs have been converted from depth to time to tie to the seismic section and then to horizons used in correlation. According to Warren (2018), DT logs are widely used for correlation and construction of synthetic seismograms. When using representative velocities in interpretation of seismic lines, it must be taken into account that the presence of bedded salt units can have an appreciable effect on the average seismic velocity through a salt interval.

Second, seismic sections of Antalya Bay have been correlated with Manavgat-2, the well closest to Antalya Bay (study area 1). Understanding the effects of changes in velocity and density on seismic reflections, particularly in the case of halite and anhydrite, helps in properly defining the MES/M reflector at the base of the Pliocene in Antalya Bay.

The correlation between onshore and offshore seismic sections and the Manavgat-2 well shows the presence of the same MES with a close correspondence between onshore and offshore areas (Figure 7).

Finally, all offshore and onshore seismic sections near and across the Manavgat-2 well were interpreted and analyzed in the Manavgat subbasin. It can be clearly seen that the MES is getting closer to the topographic surface from southwest to northeast in the Manavgat subbasin (Figure 7). All lithological units and the reverse fault can be clearly seen (Figures 8A and 8B) on the most significant seismic line that crosses the Manavgat-2 well (line C in Figure 6). Detailed examination of logs, particularly GR, DT, and CALI in the Manavgat-2 well, reveals that there is a decrease in the value of GR and DT logs at nearly 350 m in depth (Figure 8C). This trend of MES informs us about the existence of gypsum in the area but it is not precisely determined as primary or bedded-resedimented gypsum.

According to the paleontological data of Aladdin Middle East Company and interpretation of all Manavgat-2
Figure 5. A) Stratal onlaps, erosional unconformity; MES/M reflector, Quaternary, Pliocene, Lower Pliocene infill interpretation, and west-vergent thrust faults (line A in Figure 6). Te: Eskiköy Formation; Tg: Gebiz limestone; Ty: Yenimahalle Formation. B) Aksu-1 well logs. Arrows show gypsum layers with higher resistivity and low GR readings.
well logs, it was concluded that at an approximate depth between 344 and 591 m for primary and/or resedimented gypsum is present.

Because the MES is characterized by strong reflection on the basis of acoustic impedance on seismic sections as well as on well logs, in our study we proceeded to correlate all wells in the Antalya area to understand MES changes in the Aksu subbasin, offshore, and the Manavgat subbasins. The MES is also present on integrated seismic sections ranging from NW (Aksu subbasin) to SE (Manavgat subbasin) parts of Antalya Bay (Figure 9; line D in Figure 6).

In order to lithologically correlate the primary/bedded-resedimented gypsum in all three subbasins, GR, DT, and resistivity logs of Aksu-1 and Manavgat-1 have been examined. The GR, DT, and resistivity logs can be used to reliably identify the evaporites. Gypsum typically has a very low GR response and readings, and on DT logs has an interval transit time of 52.5 µs/ft. In contrast, gypsum is indicated on the resistivity log by high readings (Warren, 2018).

In the Aksu subbasin, in the Eskiköy and Gebiz Formations, gypsum is present between 411 and 487 m as indicated by low GR and high resistivity readings in the Aksu-1 well (Figure 5B).

The Taşlık Formation in the Manavgat-1 well also has low DT readings between 746 and 769 m. Likewise, Manavgat-2, as shown in Figure 8C, has low GR and DT readings between 344 and 591 m that can be interpreted as primary/resedimented-bedded gypsum. Detailed interpretations of stratigraphic and lithological summary logs and MES correlation for three onshore wells in the study area show all wells having correlatable gypsum beds indicated by the MES. Additionally, the MES in the Aksu subbasin rests directly on the Karpuzçay Formation and beneath the fluvial Eskiköy Formation, as shown in Figure 10. This MES boundary is strongly erosive, locally overlies the shallow-marine deposits of the Taşlık Formation overlain by bedded-resedimented gypsum and gypsum blocks in the Manavgat subbasin (Figures 9B and 10), and contains resedimented gypsum as shown in Çadırlıtepe and along the Alara River. In previous studies, the Messinian evaporites were only inferred in the offshore parts of the Antalya Basin (Taviani et al., 1989). Primary upper evaporite was not recorded onshore to date and was only reported as gypsum blocks. The sea-level drop associated with the MSC is marked by the shallowing siliciclastic Taşlık Formation overlain by bedded-resedimented gypsum and gypsum blocks in the Manavgat subbasin and underlain by the fluvial Eskiköy Formation in the Aksu subbasin (Figures 9B and 10).
The relationship between evaporite and nonevaporite units is explained by the Aksu phase, which caused compressional deformation leading to significant uplift in the region around the Gebiz High. This uplift also involved a relative sea-level fall, which likely resulted in primary and/or resedimented-bedded gypsum between siliciclastic deposits (Eskiköy Formation) followed by transgressive deposition of the shallow marine reefal Gebiz limestone.

Thrust faults seen in our seismic sections generally have west or southwest vergence, whereas those of the Manavgat subbasin show an east or northeast vergence (Figures 8A, 8B, and 9A). This trend in the onshore seismic sections across the Manavgat-2 well is in contrast to how it was described by Güneş et al. (2018) and Aksu et al. (2018).

The Upper Messinian-Lower Pliocene west- or northwest-vergent thrust faults, as mentioned above, together with well data and to some extent seismic sections, help us get indications on the best MES correlation (Figure 10) and gain a better understanding of the stratigraphic
and tectonic development that determined basinal topography, morphology, and development of tectonic controlled subbasins with different depositional styles.

On the other hand, Upper Messinian-Lower Pliocene tectonic activity (Figure 9) exhibits a different character in the subbasins. The Aksu subbasin was strongly affected by the thrust faults that caused uplift and erosion of the basin margin leading to lack of evaporites in the southern part of study area 3, close to the Aksu-1 well (Figure 6). However, the Manavgat subbasin (study area 2), with comparatively less tectonic activity, includes resedimented gypsum beds within the swamp environment on the fluvial deltaic deposit (Taşlık Formation).

5. Discussion
The Aksu and Köprüçay subbasins display intense deformation that resulted from west-directed compressional events of Late Miocene to Lower Pliocene age, but the Manavgat subbasin situated further east is only weakly deformed. Although the Antalya Basin evaporites have been interpreted as marginal upper evaporite (Dündar and Varol, 2016), in situ/primary evaporites are absent in the continental part of the subbasins. They are observed in restricted outcrops, collectively consisting of gypsum blocks and resedimented evaporites derived from selenite-dominated marginal/upper evaporite up to 0–200 m in depth. They were deposited in the lower-middle parts of the reefal parts of the Gebiz limestone (Figure 11).

The Manavgat subbasin is devoid of reefal accumulations, where siliciclastic sediments deposited in fluvio-deltaic environments (Taşlık Formation) are predominantly found in the Messinian succession, which is topped by gypsum conglomerate, block-size selenite, and laminated gypsum (Karabıyıkoğlu et al., 2000). The chaotic and contrasting deposition systems of the two subbasins have not been inferred from the interpretation of the offshore seismic sections, where Messinian evaporite was directly overlain by siliciclastic deposits of the Yenimahalle Formation. Poisson et al. (2011) reported that some blocks (cubic meter in volume) of massive selenite gypsum outcrops are present at the foot of the Gebiz limestone hill, to the east of the town of Gebiz. The authors have supposed that the gypsum blocks belong to a more or less continuous evaporitic layer present at about 5 to 10 m below the surface and possibly interbedded between the Messinian–Late Messinian-aged Gebiz limestone. Glover and Robertson (1998b) reported that observation of selenitic gypsum was local but not in situ and Tortonian-aged Gebiz limestone was beneath the Messinian gypsum. Similarly, Glover and Robertson (1998a) indicated that reefal limestones (Gebiz limestone) were Tortonian in age, whereas gypsum layers were Messinian in age in the Aksu subbasin.

Figure 8. A) Seismic section crossing Manavgat-2 well (line C) (without interpretation). B) MES, unit-1, unit-2, and tectonic interpretation of seismic section by using Manavgat-2 well logs (TWT: two-way travel time). C) Logs of Manavgat-2 well (arrows show gypsum layers) (MD: measured depth; CALI: caliper log; DT: sonic log; GR: gamma ray logs).
However, we believe that the gypsum blocks lying on the MES (Glover and Robertson, 1998a; Netzeband et al., 2006; Cornée et al., 2006; Stefano et al., 2010; Tekin et al., 2010; Roveri et al., 2014a, 2014b; Boulton et al., 2016) are time-equivalent to lower-middle parts of the Gebiz limestone. These gypsum blocks would have been the consequence of tectonic activity, as indicated by a number of thrust faults (mainly fault-bend folds) leading to emer-

Figure 9. A) MES/M reflector and tectonic interpretation on seismic sections of Aksu and Manavgat subbasins (line D in Figure 6) (study areas 2 and 3). B) Upper Messinian-Lower Pliocene basinal and tectonic configuration of the studied area; Aksu and Manavgat subbasins (modified from Alkan, 1999).
gence and erosion of a subsurface gypsum formation and then reworked into different lithological units of the sub-basins (Figure 12). In the Manavgat subbasin, the resedimented evaporites rest directly on the fluvio-deltaic siliciclastic unit (Taşlık Formation) without Gebiz limestone. This contrasting setting between the two subbasins (AS and MS) would be the result of different basinal morphology induced by regional tectonics (Aksu thrust).

In the Aksu subbasin, irregular basinal topography facilitates the colonization of the patch reef on the paleohills that developed after initial siliciclastic deposits (Eskiköy Formation). This reefal setting is similar to Koronia limestone in Cyprus, developed on up-faulted blocks, where most of the fore-reef facies and associated clastic input was shed into a down-faulted basinal depocenter (Follows, 1992). However, the Manavgat subbasin is devoid of carbonate-siliciclastic transition and reefal environment. Although the subbasin is relatively far from the tectonic region, it received a high rate of siliciclastic materials fed by fluvio-deltaic systems, which prevented reefal carbonate sedimentation. This contrasting deposition character would be an indication of a shifting tectonic margin and depocenter from west (Aksu subbasin) to east (Manavgat subbasin). Consequently, the Taşlık Formation, which is time-equivalent to the Gebiz limestone and Eskiköy Formation, is directly overlain by resedimented gypsum without Gebiz limestone in onshore outcrops. Çiner et al. (2008) pointed out that the coralgal reefs, which occur as small, isolated patch reefs, developed on progradational alluvial fan/fan delta conglomerates, and the reefal shelf carbonates represent small- to large-scale transgressive-regressive cycles that are closely associated with the complex interaction between sporadic influxes of coarse terrigenous clastics derived from the tectonically active basin margins and/or related to the eustatic sea level changes during Late Burdigalian-Langhian and Late Tortonian-Messinian times (Figure 2). However, the authors did not point out any evaporite outcrops in the Aksu and Manavgat subbasins.

We conclude that the tectonic emplacement of the resedimented gypsum conglomerates and blocks could be the result of the final stage of the basinal compressional regime and consequent thrusting activities. This regime ended by the Late Messinian transgression/extension culminating in Early Pliocene siliciclastic deposition (Yenimahalle Formation). This unit is composed of different kinds of siliciclastic accumulation of the shore-delta complex. It also contains gravelly incises within a

![Figure 10. Correlation of Aksu-1, Manavgat-1, and Manavgat-2 wells (modified from Alkan, 1999).](image-url)
muddy estuarine environment. Similar Tortonian and Messinian syntectonic activity took place in the Eastern Betic basins (Krijgsman et al., 2006) and in other parts of the Mediterranean (e.g., Aksu et al., 2005). Several phases of synsedimentary tectonic activity deforming individual Messinian evaporitic successions have been reported from the Levantine Basin, and Cyprus and southeastern Turkey (Glover and Robertson, 1998a; Netzeband et al., 2006; Tekin et al., 2010; Boulton et al., 2016). This forms compelling evidence for a major change in the Messinian plate kinematic framework (Molenaar, 2007). Additionally, the clastic nature of part of the Messinian evaporite deposits was recognized earlier, e.g., in the Sicilian basins (Schreiber et al., 1976), but it has long been ignored. Recent studies reveal that the Mediterranean never dried up (Roveri et al., 2001; Matano et al., 2005) and the evaporite deposits in the deep basins are cannibalized shallow-marine evaporites (Manzi et al., 2005; Roveri and Manzi, 2006; Roveri, 2008). Deposition in deeper basins by mass-flow mechanisms such as turbidity current flows, submarine debris flow, and large-scale slides-slumps is in full agreement with the well-documented Messinian tectonic activity (e.g., Molenaar, 2007).

6. Conclusion
Interpretation of seismic sections shows the presence of unit 1 (Quaternary and Yenimahalle formation), unit 2 (Gebiz limestone, Eskiköy and Taşlık Formations, and Messinian evaporites) and the MES/M reflector, and their continuity, thicknesses, and the onshore location where MES evaporites actually outcrop. Messinian evaporite successions are very thin in the shallower part of offshore Antalya Bay (140 m) and onshore (40 m), but their corresponding thickness is about 500 m in the deeper parts of the studied area.

Structural interpretation of seismic sections indicates that Late Messinian-Early Pliocene compression is expressed by W- and SW-vergent thrust faults (Aksu phase) and by reactivation in the Aksu subbasin that caused accompanying erosions, regression and transgression, and reworking processes, and by the presence of deep incisions and canyons. However, the Manavgat subbasin W-E, SW-NE oriented thrust fault seen in seismic sections can explain the different depositional characters of the subbasins.

In the Aksu subbasin, gypsum blocks are time-equivalent to lower-middle parts of Gebiz limestone and indicate an allochthonous (reworked) setting transported from Messinian upper gypsum during the early uplifting of the basin margin. The evaporite erosion was marked by the MES in the seismic sections. The MES/M reflector is characterized by a strong reflector and acoustic character easily traceable through the area. Gebiz limestone was accumulated on the topographic highs developing as
local and small carbonate platforms with patch reefs and rhodolite-bearing algal flats. The Pliocene started with a new depositional regime characterized by prograding delta and siliciclastic shore.

Gebiz limestone is not deposited in the Manavgat subbasin. Resedimented gypsum is present in the upper part of the fluvio-deltaic Taşlık Formation, which is nearly time-equivalent to the Gebiz limestone and underlying the Eskiköy Formation. The resedimented evaporite unit consisting of gypsum conglomerates, selenite, and laminated gypsum blocks was covered by coal-bearing mudstone, mostly composed of coal and plant fragments.

Figure 12. Basinal and tectonic configuration of a relatively deeper part of the Aksu subbasin on seismic section. Fault-bend fold by thrust movement (Cosgrove, 2015).
with Upper Miocene (Messinian) foraminifera and palynomorphs. The Yenimahalle Formation (Pliocene) was continuously deposited after evaporite-bearing Late Miocene siliciclastics (Taşlık Formation), represented by shore siliciclastics with incised conglomerate and local estuarine mudstone. The different depositional characters of the subbasins (Aksu and Manavgat) and erosion of the marginal evaporite basins were controlled by thrust activity of the Aksu tectonic phase from the Tortonian to Early Pliocene.

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