

Synsedimentary metre-scale normal faults within turbidites of Miocene submarine fans in the Adana Basin, southern Turkey – implications for their origin

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Abstract

This study investigates the origin, geometry, and deformation of faults in turbidite deposits that form submarine fans of the upper Burdigalian–lower Serravallian Cingöz Formation, in the Adana Basin, southern Turkey, as revealed in newly exposed road cuts. Field observations indicate their synsedimentary origin based on two principal criteria: (i) undeformed younger units of the same formation overlie the faults, (ii) younger beds in a local area are flexurally deformed into a hanging-wall depression, forming a monoclinial, step-like fold, with the remaining part of the depression above the fold subsequently infilled by locally reworked intraformational sediments. The faults predominantly occur within sandstone-dominated middle-fan deposits. They are high-angle normal faults with preferred orientations in two principal directions and generally occur as single structures; however, some appear as parallel synthetic faults or as paired faults forming small-scale horst and graben geometries. The displacement of the faults is often uncertain due to the absence of marker horizons. Nevertheless, a displacement of 10–15 cm was measured on one fault pair, and an estimated displacement of 4.8 m was identified on another fault. The faults exhibit zones of variable width, some of which contain breccia and cataclastic infill. Deformation features associated with faulting include drag folds, secondary faulting within shear zones, and monoclinial flexural collapse. Within a broader tectono-sedimentary framework, we propose that deeper-seated faults at the base of the foreland basin indirectly controlled the development of these synsedimentary structures. The faults probably occur due to tectonic subsidence of the basin, which is facilitated when the sediment achieves sufficient consolidation by the weight of the overlying deposits.

Keywords: Syndepositional faulting, early-stage consolidation, Cingöz Formation, deep-sea fans, foreland basin

1. INTRODUCTION

Synsedimentary faults, which develop contemporaneously with sediment accumulation, provide critical constraints on basin evolution by recording the direct interaction between tectonic processes and sedimentation (LUXING et al., 2020; YANG et al., 2023). Synsedimentary faults have been observed and documented, especially in turbiditic deposits, particularly within turbiditic successions (ANDERTON, 1979; POCHAT & VAN DEN DRIESSCHE, 2007; SHAN et al., 2020; JAMIL et al., 2021) and deltaic deposits (XIA et al., 2018; LUXING et al., 2020; YANG et al., 2023). They have also been detected in seismic studies (e.g., JAMALUDIN et al., 2014; XIA et al., 2018; SONG et al., 2021). In addition, a few studies report synsedimentary faults in carbonates (CARDELLO & MANCKTELOW, 2014; JAMALUDIN et al., 2014). Despite extensive documentation, the origin of synsedimentary faults remains a matter of controversy. Their development has been attributed to a variety of interacting factors, including sediment overburden pressure, pore-fluid overpressure, tectonic stresses, the influence of pre-existing lithologies and structures, and seismic activity (PICKERING, 1983; CHILDS et al., 2003).

In contrast to other well-studied settings, synsedimentary faults within the Miocene deep-marine clastic deposits of the

Cingöz Formation have not previously been documented in detail, largely due to limited exposure and poor visibility. However, these structures have recently been exposed by newly excavated road cuts, providing a unique opportunity for direct field-based investigation. This study documents these newly exposed sections to characterize the geometry, distribution, and kinematic features of the synsedimentary faults and to evaluate their origin within a regional tectono-sedimentary framework.

2. GEOLOGICAL SETTING

The study area is located in the north of the Adana Basin and forms a Neogene basin in the Tauride orogenic belt (Fig. 1; YALÇIN & GÖRÜR, 1983; GÜRBÜZ & KELLING, 1993). There is a sedimentary succession in the Adana Basin, up to 6 km thick, spanning in age from the Burdigalian to the Recent and unconformably overlying the pre-Miocene basement rocks (YALÇIN & GÖRÜR, 1983; YETİŞ et al., 1995). The basement rocks consist of Upper Palaeozoic carbonates and shales, Mesozoic carbonates, and an Upper Cretaceous allochthonous ophiolitic complex (GÜRBÜZ & KELLING, 1993).

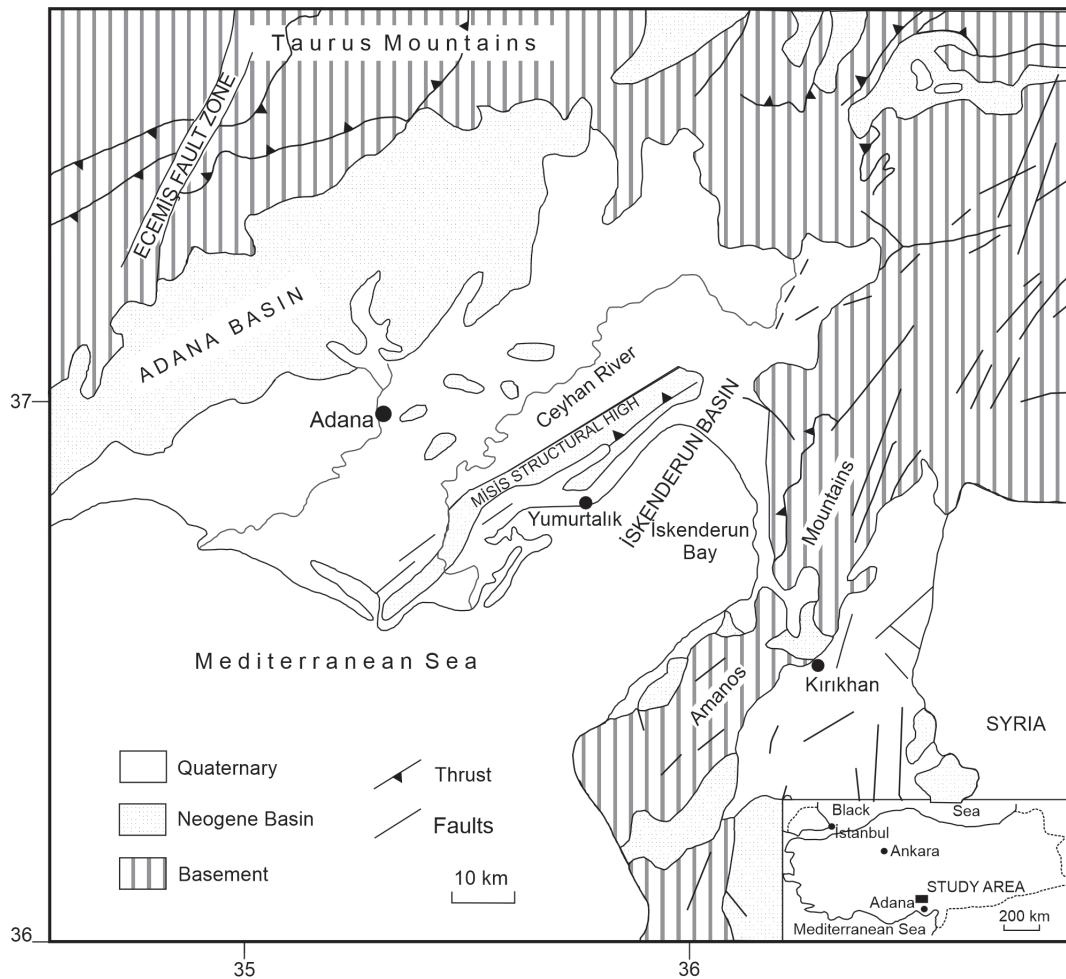


Figure 1. A simplified tectonic map of the eastern Mediterranean showing the location of the study area within the Adana Basin (GÜRBÜZ, 1999; GÜRBÜZ & KELLING, 1993)

The Neogene stratigraphic succession, from older to younger, comprises the following formations: the Karsanti (fluvial–lacustrine; predominantly marl and mudstone), the Gildirli (terrestrial fluvial deposits composed of conglomerate, sandstone, and shale), the Kaplankaya (slope deposits including siltstone, marl, clay, and sandstone), the Karaisalı (reefal limestone), the Cingöz (turbidites), the Güvenç (deep- to shallow-marine marl and foraminifer-rich shale), and the Kuzgun (fluvial to shallow-marine and lacustrine sandstone and mudstone) (Figs. 2, 3). Basement topography, together with relative sea-level fluctuations, exerted a primary control on Miocene sedimentation, leading to pronounced lateral and vertical facies variability within the basin (YALÇIN & GÖRÜR, 1983).

The Cingöz Formation is extensively exposed in the northern Adana Basin and consists of upper Burdigalian – lower Serravallian deep-marine turbidites with thicknesses ranging from ≈1,000 to 3,000 metres (NAZİK & GÜRBÜZ, 1992; GÜRBÜZ et al., 1998; SILVA et al., 2020). Within this deep-sea clastic system, two sand-rich submarine fans developed (Fig. 2; YETİŞ, 1988; GÜRBÜZ & KELLING, 1993; YETİŞ et al., 1995; GÜRBÜZ et al., 1998; GÜRBÜZ, 1999; SILVA et al., 2020). Each fan was fed by channelized inner-fan deposits and displays upward-thickening middle-fan lobes, overlain by lower-fan to basin-plain sediments, forming

depositional cycles of alternating sandstone and siliceous mudstone. Notably, the thickness and grain size of the sandstone layers gradually decrease laterally basinwards, while simultaneously, the mudstone layer thickness increases correspondingly. Sedimentary supply was provided by multiple northern feeder channels in the eastern fan, whereas the western fan was predominantly fed by a single western channel (SILVA et al., 2020).

3. MATERIALS AND METHODS

Detailed field investigations were conducted on 32 synsedimentary faults at 19 locations within the Cingöz Formation. Data collection focused on fault geometry, orientation, displacement, and fault-zone architecture. Fault orientations were statistically evaluated using rose-diagram analysis to identify dominant fault trends, and the spatial distribution of faults was assessed in relation to depositional facies across the outcrop belt.

4. RESULTS

4.1. Field description

Synsedimentary faults are most frequent within the eastern middle-fan lobe of the Cingöz Formation (Figs. 2, 4a–g) and occur less commonly in lower-fan to basin-plain deposits (Figs. 2, 4h). Middle-fan turbidite deposits are predominantly

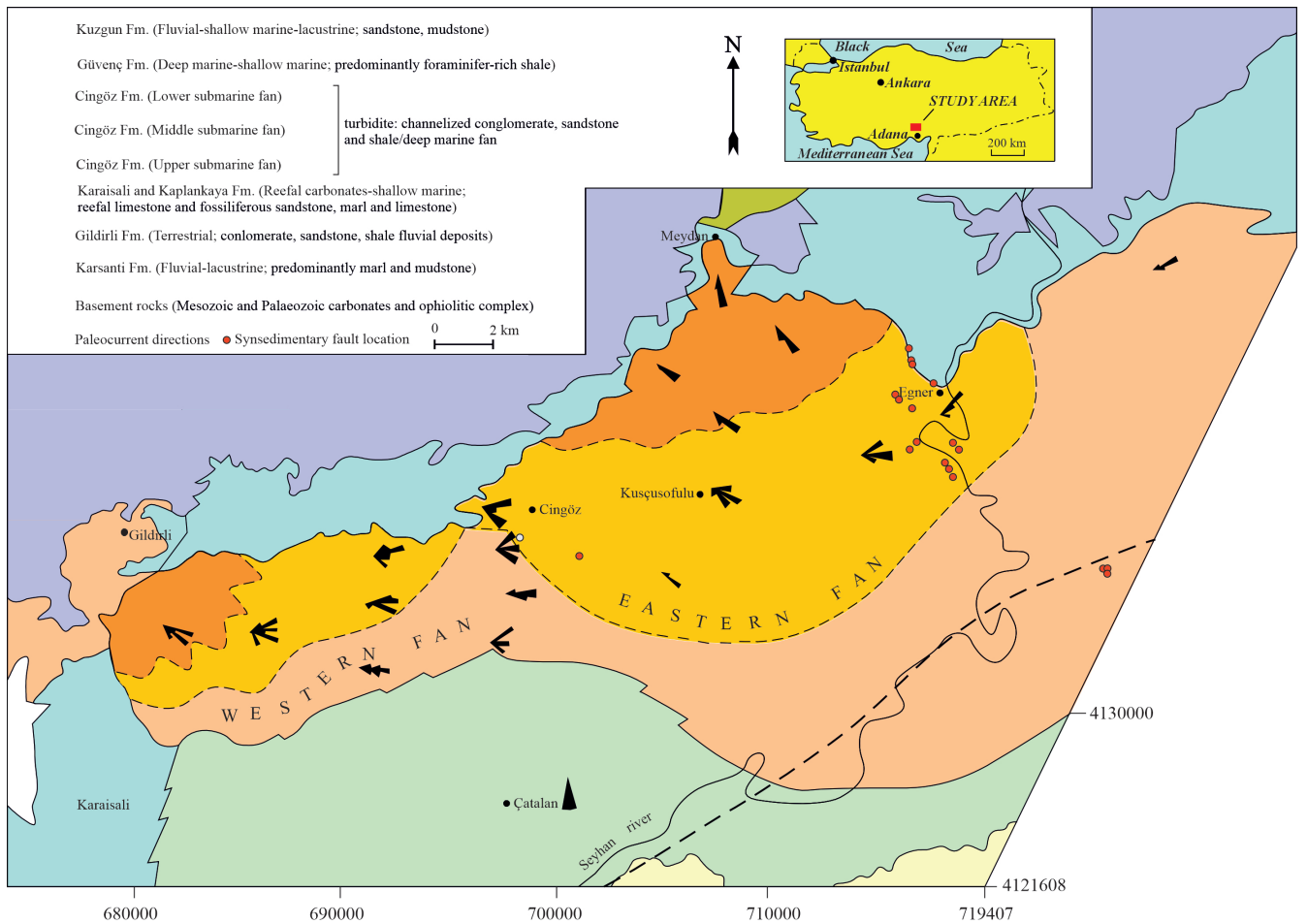


Figure 2. A geological map of the study area showing two submarine fans in the northern part of the Adana basin and their subdivisions (modified from GÜRBÜZ, 1999; GÜRBÜZ & KELLING, 1993).

| Ma | AGE | FORMATION | LITHOLOGY | LITHOLOGY/ ENVIRONMENT | |
|----|-------------------------|-------------|--------------------------|---|--|
| | QUATERNARY | RECENT | | hardpan calcrete/alluvium alluvial terrace | |
| 5 | PLIOCENE U L | HANDERE | | predominantly mudstone, conglomerate and sandstone/ shallow marine, lagoon and fluvial | |
| | | | | | Messinian |
| 10 | MIOCENE W Z | Tortonian | KUZGUN | | sandstone, mudstone/ shallow marine to non-marine |
| | | Serravalian | GÜVENÇ | | predominantly foraminifer-rich shale deep to shallow marine |
| 15 | C O | Langhian | CİNGÖZ | | turbidite: channelized conglomerate, sandstone and shale/deep marine fan |
| | | Burdigalian | *KARAIŞALI KAPLANKAYA | | *reefal limestone/shallow marine fossiliferous sandstone, marl and limestone coastal to shallow marine |
| 20 | Aquitanian | **GİLDİRLİ | | **conlomerate, sandstone, shale fluvial deposits | |
| 28 | OLIGOCENE | KARSANTI | | predominantly marl and mudstone alluvial-lacustrine-lagoonal | |
| | MESOZOIC- PALAEOZOIC | BASEMENT | | ophiolitic complex (Upper Cretaceous) Mesozoic and Palaeozoic carbonates not to scale | |

Figure 3. A stratigraphic column of the northern part of the Adana Basin (modified from GÜRBÜZ, 1999).

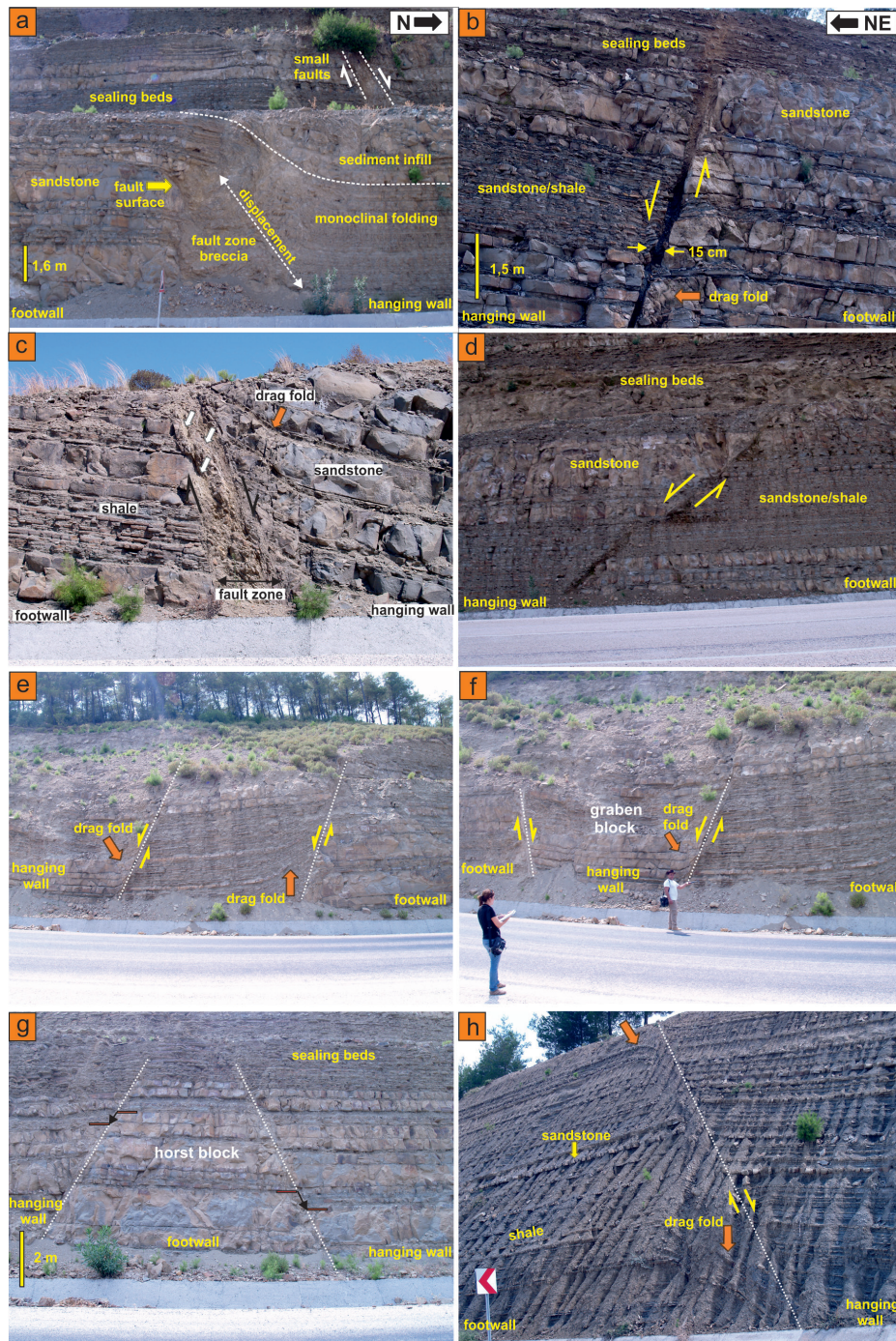


Figure 4. Field photographs of selected synsedimentary normal faults within the submarine fan turbidites of the Upper Burdigalian–Lower Serravallian-aged Cingöz Formation: (a) a normal fault with a dip of 78° exhibits a footwall block dominated by medium to thick-bedded sandstones interbedded with thin layers of mudstone. The uppermost part of the sediment sequence was deformed as a result of faulting, forming a step-shaped monoclinial flexural fold. These sediments consist of alternating thin-bedded sandstone and mudstone on the hanging wall. Later, a depression formed in the upper part of the hanging wall above the step-like fold containing a chaotic fill of locally reworked sandstone blocks surrounded by fluidized muddy sediments. Finally, younger turbiditic thin beds of sandstone and mudstone seal the fault and all associated deformational structures. There is a slickenside lineation in a small preserved part of the fault surface. The fault zone breccia consists of angular sandstone blocks of various sizes and a sandy-clay-rich matrix between them, and shows shear effects. The fault zone narrows upward. The displacement of the fault is uncertain due to the absence of marker layers, but the estimated displacement is 4.8 m from the monoclinial fold. This photograph also shows a small fault (dotted lines) associated with fault breccia between the white arrows in the sealing beds; (b) a typical high-angle fault inclined at 67° that passes through turbidite deposits composed of alternating thin to medium bedded sandstone and mudstone. The fault zone, which is 5.5 m long and 15 cm wide, consists mainly of sandstone and mudstone clasts in the sand and fine gravel grain size range; (c) a strongly inclined (76°) fault in sandstone-dominated turbidites with secondary small faults in the fault zone (yellow arrows). The fault zone narrows upwards and shows shear effects. At the fault contact, the layers exhibit bending or drag fold structures (orange arrow); (d) a normal fault with a dip of 42° within a thin- to medium-bedded sandstone- mudstone alternation; (e) steeply dipping synthetic normal faults (dotted lines) intersecting the sandstone–mudstone alternation. The beds show bending at the fault contact; (f, g) pairs of steeply dipping normal faults dipping towards the central block to form a graben structure (f) and dipping away from the central block to form a horst structure (g). The sequence in (g) denotes a fining-upward pattern. There is bending in the beds at the fault contact (orange arrow); (h) normal fault (dotted line) developed in lower fan or basement deposits dominated by mudstone with interlayers of fine sandstone. Movement along an inclined fault plane produced drag folds (orange arrows).

composed of medium- to thick-bedded sandstones interbedded with fine-bedded mudstones, which gradationally pass upward into thin-bedded sandstone–mudstone alternations (Fig. 4a–g). In contrast, the outer fan deposits are dominated by mudstones containing thin sandstone interlayers (Fig. 4h).

The syndimentary faults are typically several metres long and consist mainly of steeply dipping normal faults with variable orientations (Figs. 4, 5b). Rose diagram analysis indicates moderately developed preferred fault orientations, with dominant NE–SW- and NW–SE-trending fault sets (Fig. 5a). Displacement along the faults is often difficult to ascertain due to the absence of marker beds. However, displacement of 10–15 cm was measured on one fault pair (Fig. 4g) and up to 4.8 m on another (Fig. 4a). Most structures occur as individual faults; nevertheless, parallel synthetic faults and fault pairs dipping toward or away from intervening blocks are also observed, locally giving rise to small-scale graben and horst structures.

Fault zones vary from discrete fault-surface traces to zones up to 1.8 m wide and are locally filled with breccias composed of angular sandstone fragments supported by a sandy to clayey matrix. The layer sections adjacent to fault surfaces commonly exhibit drag folds, indicating the sense of fault slip (DAVIS, 1984). Furthermore, the faults are overlain by undeformed younger turbidite beds of the same formation (Fig. 4), indicating that faulting predates the deposition of these strata.

In addition to brittle deformation, faulting also resulted in flexural bending of younger strata into hanging-wall depressions, forming a monoclinical, step-like fold; the remaining

part of this depression was subsequently infilled by locally reworked intraformational sediments associated with soft-sediment deformation within the mudstone (Fig. 4a).

5. DISCUSSION

The submarine fan turbidite deposits of the upper Burdigalian – lower Serravallian Cingöz Formation in the Adana Basin were deposited in a deep marine environment (YETİŞ, 1988; GÜRBÜZ & KELLING, 1993; YETİŞ et al., 1995; GÜRBÜZ et al., 1998; GÜRBÜZ, 1999; SILVA et al., 2020). Within this depositional framework, three facies representing different depositional zones of a submarine-fan system—namely the inner-, middle-, and outer-fan—were identified within the Cingöz Formation (YETİŞ et al., 1995). Field observations reveal that syndimentary faults are preferentially developed within middle-fan deposits, whereas they are markedly less common in the mud-dominated lower-fan and basin-plain settings. This facies-controlled distribution indicates that fault development was strongly influenced by lithological heterogeneity and mechanical stratigraphy during early burial.

A syndimentary origin for the faults is supported by two independent field-based criteria: (i) the faults are consistently sealed by younger, undeformed turbidite beds of the same formation, indicating that fault activity was contemporaneous with sedimentation (Fig. 4; BERGERAT et al., 2011); and (ii) faulting locally resulted in flexural bending of the immediately overlying beds into a hanging-wall depression. The subsequent infill of this depression by reworked intraformational material provides direct evidence for syn-depositional seafloor deformation (Fig. 4a). Fault-associated deformation features,

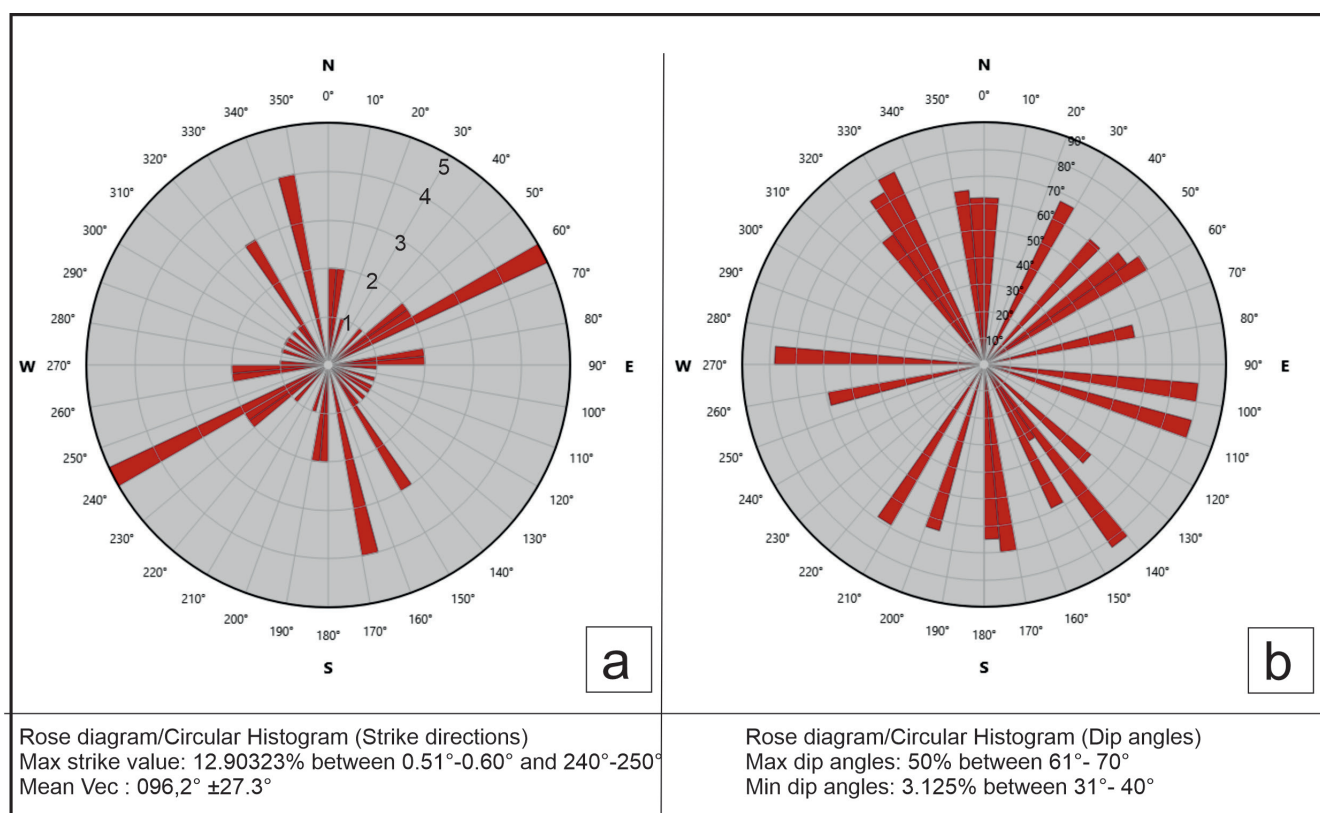


Figure 5. Rose diagrams illustrating the strike and dip characteristics of syndimentary faults ($n = 32$) within the Cingöz Formation. (a) Strike data indicate dominant NE–SW- and NW–SE-trending fault sets; (b) most faults exhibit moderate to steep dip angles, typically ranging between 60° and 70°.

including drag and monoclinical flexural folds, further demonstrate that these structures represent normal faults formed under predominantly extensional conditions (Fig. 4).

The pronounced concentration of synsedimentary faults within middle-fan environments, compared to their scarcity in more distal depositional settings, highlights the role of differential sediment loading in fault development. Middle-fan lobes are typically characterized by high sedimentation rates and elevated sand-to-mud ratios (NORMARK, 1978; SHAN et al., 2020). The rapid accumulation of relatively dense sandstone bodies onto poorly consolidated, mud-rich substrates likely promoted gravitational instability and differential compaction, thereby facilitating fault initiation. The coexistence of brittle faulting with ductile flexural deformation implies that deformation occurred during an early stage of sediment consolidation, prior to complete lithification of the turbidite succession.

The occurrence of normal faults dipping in different directions, together with opposite dipping fault pairs, locally results in the development of small-scale graben and horst geometries within middle-fan deposits. Such geometries reflect a distributed extensional strain field, rather than progressive block rotation or unidirectional tilting. This fault architecture is characteristic of synsedimentary deformation in partially consolidated sediments, where strain is accommodated by both synthetic and antithetic normal faulting.

Within the broader geodynamic framework of southern Anatolia, the development of the Adana Basin is closely linked to convergence between the African/Arabian and Eurasian plates (ŞENGÖR et al., 1985; HEMPTON, 1987). Numerous tectonic models have been proposed to explain the initiation and evolution of the basin (CIPOLLARI et al., 2013; SILVA et al., 2020), with most studies converging on the interpretation that the basin functioned as a subsiding foreland basin during the Miocene, driven primarily by thrust-sheet loading from the Taurus orogenic belt (ÜNLÜGENÇ, 1993; WILLIAMS et al., 1995).

Our results are broadly consistent with seismic reflection interpretations (WILLIAMS et al., 1995; GÜRBÜZ, 1999), which document two dominant fault orientations (NNW–SSE and NW–SE) within the basin. However, the field-based evidence presented here refines these models by demonstrating that, although deeper-seated basement structures may have exerted an indirect control on fault orientation, the faults themselves nucleated and evolved within the turbidite succession during early burial. This tectono-sedimentary setting, characterized by ongoing basin subsidence and rapid sediment loading, provided an extensional stress regime that promoted brittle deformation within a partially consolidated basin fill.

6. CONCLUSION

The Cingöz Formation in the Adana Basin consists of submarine-fan turbidites deposited in a deep-marine environment and is dated to the upper Burdigalian–lower Serravallian. Synsedimentary faults are widespread within sandstone-dominated middle-fan deposits, where they typically occur as steeply dipping normal faults with two principal orientations

and locally form small-scale horst and graben geometries. Field relationships, such as sealing by younger strata, monoclinical step-like folding, and fault-zone infill derived from adjacent, poorly consolidated sediments, indicate synsedimentary faulting during sediment accumulation and early burial.

The development of synsedimentary faults reflects the combined influence of depositional processes, lithological contrasts, and regional tectonic stresses. High sedimentation rates and mechanical contrasts within middle-fan deposits promoted fault localization, while regional extensional stresses associated with foreland-basin subsidence provided the broader tectonic framework. Basement-controlled deformation likely exerted an indirect influence on the basin floor, facilitating normal faulting once the sediments reached a semi-consolidated state. These results highlight the close coupling between sedimentary processes and tectonic deformation in the evolution of submarine-fan systems within foreland-basin settings.

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