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The geodynamic evolution of Pindos foreland basin in SW Greece

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The distribution of Eocene-Oligocene turbidite facies in the Pindos foreland and the paleocurrent directions of submarine fan deposits, of the Peloponnese area, document the proximal part of an underfilled foreland basin. The definition of Pindos foreland basin attributes sediment accommodation solely to flexural subsidence driven by topographic load of the thrust belt and sediment loads in the foreland basin. The restriction of the coarse grained deposits and the basin underfilled conditions are related to the Pindos foreland evolution, and especially to the internal thrusting and produced intrabasinal highs. The presence of strike-slip faults can affect the geometry of a basin by causing changes in depth and width, resulting in the transformation from a uniform to non-uniform configuration. This change has an intensive impact on depositional environments along the basin axis. Strike-slip faults that cross-cut intrabasinal highs produce pathways for the sediment distribution on both sides of the highs. Distributary channels that discharge into the basin are perpendicular to its axis and shift axially at the basin floor. The strike-slip and thrust faulting operated contemporaneously for much of their active periods, although it appears that thrust faulting, initiated slightly earlier than strike-slip faulting.

Introduction

The interplay of base level changes and sediment supply controls the degree to which the available accommodation is consumed by sedimentation. This defines the underfilled, filled and overfilled stages in the evolution of the foreland system, in which depositional processes are dominated by deep marine, shallow marine, or fluvial sedimentation, respectively (Sinclair and Allen, 1992). The change from underfilled to overfilled stages is best observed in the foredeep, because the forebulge may be subject to erosion in the absence of (sufficient) dynamic loading, or, at most, it may accommodate shallow marine to fluvial environments even when the foredeep is underfilled. Appropriate ways to describe the stratigraphic fill and study the basin evolution in foreland basins have been looking for several decades. The principal control on stratigraphic stacking patterns of foreland

basins is a matter of question, such as eustasy, orogenic loading, erosion and deposition, dynamic topography, intraplate stress, basement reactivation. The sedimentary fill records interplay between regional tectonics, eustasy and normal sedimentary processes (Beaumont, 1981; Allen *et al.*, 1986). Much effort has gone into the modelling of foreland basins using various techniques (e.g. Allen *et al.*, 1986; Stockmal and Beaumont, 1987; Sinclair, 1997; Allen *et al.*, 2001; Rafini and Mercier, 2002; Clevis *et al.*, 2004; Bera *et al.*, 2008; Bera *et al.*, 2010; Roddaz *et al.*, 2011). The resulting models have focused on the proximal part of foreland basins, where the effects of lithospheric loading are pronounced close to the overthrust load, and where deep-water ‘flysch’ and late-orogenic ‘molasse’ predominate. Sublithospheric “loading” of the overriding plate is primarily caused by the drag force generated by viscous mantle corner flow coupled to the subducting plate, especially where subduction is rapid and/or takes place at a shallow angle beneath the retroarc foreland basin (Mitrovica *et al.*, 1989; Gurnis, 1992; Holt and Stern, 1994; Burgess *et al.*, 1997). Excepting for dynamic loading, all other types of supra- and sublithospheric subsidence mechanisms relate to the gravitational pull of “static” loads represented by the subducting slab, the orogen, or the sediment-water mixture that fills the foreland accommodation created by lithospheric flexural deflection. The static tectonic load of the orogen and the sublithospheric dynamic loading are most often invoked as the primary subsidence mechanisms that control accommodation and sedimentation patterns in retroarc foreland settings (Beaumont *et al.*, 1993; DeCelles and Giles, 1996; Pysklywec and Mitrovica, 1999; Catuneanu *et al.*, 1999a,b, 2002). However, proximal parts of foreland basins are commonly deformed or partly obscured by the overthrust load. Also, the relative effects of tectonics versus eustatic sea-level change and normal (i.e. autocyclic) sedimentation may not be easy to untangle in such deep-water “flysch” basins.

This paper provides a case study for the sedimentation patterns that may develop in an underfilled forearc foreland system, under a unique combination of factors that control the dynamics of the basin and the amounts of available accommodation. We focus on the Eocene-Oligocene sedimentation of the Pindos foreland basin of south-west Greece, which we interpret as part of the proximal area of a foreland basin related to the final closure of the Pindos Ocean. The Pindos foreland basin is an example of Tertiary turbidite basin fill, segmented during its evolution by propagating thrusts. The distribution of turbidite facies in the Pindos foreland and the palaeocurrent directions of submarine fan development show that the southern part of the Pindos foredeep, from the late Eocene to the early Oligocene, was an example of underfilled foreland basin. The study area is an excellent example of an underfilled foreland basin in order to study processes affecting the proximal part of a foreland basin and its

development through time. It has been shown that the Eocene-Oligocene succession in the southern Pindos foreland basin, Peloponnesus peninsula, consists of several-million-year tectonically-driven cycles comprising strata deposited in an underfilled basin with a prominent forebulge zone. The Late Eocene strata and the early Oligocene strata were deposited in underfilled conditions and could be interpreted in terms of the expected syntectonic subsidence pattern of a foreland basin system, respectively. Isopach values increasing towards the Pindos Mountain fold-thrust belt may be interpreted as representing sedimentation in the foredeep zone. A linear trend of low values indicates the presence of the forebulge zone. Therefore, the three studied sub-basins in southern Greece provide an opportunity for an in-depth study of the mechanisms of the forebulge migration and stratigraphic fill of the forebulge depozones in Pindos foreland basin. In the following we proposed a qualitative model for the Pindos forebulge migration and the stratigraphic fill of this underfilled foreland basin.

Geological setting

The convergence and collision of the Eurasian and African Plate margins in the Paleocene - early Tertiary formed the Hellenide orogen (Robertson and Dixon, 1984; Dercourt *et al.*, 1986; Savostin *et al.*, 1986). The Hellenides are generally interpreted as a thrust stack (Smith and Moores, 1974) resulting from a SW-propagating fold-and-thrust

system (*sensu* Boyer and Elliott, 1982). The external Hellenides consist from east to west of the Pindos, Gavrovo, Ionian and Pre-Apulia geotectonic Zones (Aubouin, 1959). These zones are generally bounded by east- to NE-dipping Tertiary thrust faults. Pindos foreland is a tertiary turbiditic basin-fill trending parallel to the external Hellenides (Aubouin, 1959) and occupies Gavrovo and Ionian geotectonic zones. The basin is bounded to the east by the Pindos thrust and to the west by the Ionian thrust (Figure 1A, B). Apart of these two major thrusts, minor thrusts (Gavrovo, internal and middle Ionian thrusts) separate the basin into linear narrow sub-basins, trending parallel to the basin axis.

Turbiditic accumulation resulted from the deformation of the external Hellenides which migrated westwards. During the Eocene/Oligocene, eastward subduction of the Pindos Ocean resulted in deep-sea sedimentary lithologies being detached from their oceanic igneous basement as an accretionary prism and emplaced westwards onto the adjacent carbonate platform, ending up as a series of thin-skinned thrust sheets (Degnan and Robertson, 1998). Studied basin during Miocene changed to a backstop basin (Le Pichon *et al.*, 2002) due to outward migration of the Hellenic nappes between 20 and 15Ma. The present accretionary wedge then would be the post -Middle Miocene.

The Pindos thrust activity formed a foredeep during Middle Eocene (IGSR & IFP, 1966), in the pre-existing area of Gavrovo and Ionian zones (Underhill 1985, Brooks *et al.*, 1988; Underhill, 1989;

Figure 1. A Geological map of Greece showing the study area, in Peloponnesus peninsula, modified after Bornovas and Rontogianni-Tsiabaou (1983). B Simplified geological map of the three studied sub-basins showing major geological units where the turbidite deposits were mapped.

Clews, 1989; Alexander, 1990), whereas due to the internal thrusting, during the Late Oligocene the foreland changed to a complex type foreland basin, in its northern part (Avramidis *et al.*, 2002), and during Early Pliocene to a piggy-back basin, in the southern Zakynthos area (Zelilidis *et al.*, 1998). The Pindos foredeep, during the middle Eocene to late Miocene, was filled by submarine fan deposits (Pavlopoulos, 1983; Alexander, 1990; Leigh and Hartley, 1992), and the submarine fans source was the forehead of Pindos thrust (Piper *et al.*, 1978; Faupl *et al.*, 1998; Fleury, 1980; Clews, 1989; Wilpshaar, 1995). Strike-slip faults acting synchronously with the main thrusts influenced the evolution of the Pindos foreland and consequently the evolution of depositional environments. (King, 1993; Avramidis, 2001; Avramidis *et al.*, 2002). Strike faults cross-cut the Pindos thrust and so its activity took place independently in different parts and in different times, during early Eocene in Ioannina area, during late Eocene in Arta area and during early Oligocene in Mesologgi area (Vakalas, 2003). Moreover, strike-slip faults many times acted as pathways influenced the paleocurrent network, discharging sediments in more distal areas (Zelilidis *et al.*, 2008).

Palaeomagnetic evidence shows that the litho-tectonic zones of

the Hellenides in southern Greece, including the studied area, underwent regional tectonic rotation, associated with the formation of the southward-convex Aegean arc (Kissel and Laj, 1988). As a result, the present-day configuration of nearly N-S-trending tectonic units was orientated more east-west during Mesozoic-early Tertiary time.

Depositional environments

In order to study the basin fill conditions of the Pindos foreland in Peloponnese peninsula, we focus on the turbidite deposits of three sub-basins (Figure 2):

Tritea sub-basin

The total thickness of the studied submarine fan deposits is up to 1100m (Figure 2A, 3A). Lithologies include conglomerates, sandstones and mudstones. The transition from carbonatic to clastic sedimentation took place from Priabonian (Late Eocene) (NP19–NP20) (*sensu* Martini, 1971; Berggren *et al.*, 1995), as indicated by

Figure 2 A proposed model of the Pindos foreland evolution in Peloponnese peninsula, during Late Eocene-Early Oligocene time. A Geological map of Tritea basin showing the geological units whereas the numbers show the studied outcrops. B Geological map of Hrisovitsi basin. The numbers show the studied outcrops. C Geological and outcrop map of Finikounda basin showing the studied turbidite deposits.

Figure 3. A Stratigraphy of Late Eocene-Early Oligocene deposits in Tritea basin. Rose diagrams of the paleocurrent directions at the various stratigraphic levels are plotted. Noted the variations in facies distributions and the alternating packages of channel-fill and lobe deposits. Lithofacies: CF=channel-fill deposits; IC=interchannel deposits; LV=levee; LB=lobes; SI=slope deposits. Elements: No= number of data; Vm= vector mean. B Detailed sedimentological log of Late Eocene-Early Oligocene turbidite deposits in Hrisovitsi basin. The palaeoflow directions have been plotted in rose diagrams. Lithofacies: CF=channel-fill deposits; IC= interchannel deposits; LV= levee. Elements: No= number of data; Vm= vector mean.

Figure 3. C Stratigraphy of Late Eocene-Early Oligocene turbidite deposits in Finikounda basin. Red arrows show the paleocurrent directions. Rose diagrams of the paleocurrent directions at the various stratigraphic levels are plotted. Lithofacies: CF=channel-fill deposits; LV= levee; LB= lobes; LF=lobe-fringe deposits; IL= inter-lobe deposits; CG= conglomerates. Elements: No= number of data; Vm= vector mean.

nannofossil markers (*Reticulofenestra bisecta*, *R. umbilica*, *R. samodurovi*, *R. oamaruensis*, *R. ovata*, *R. hillae*, *R. scrippsae*, *Discoaster saipanensis*), and lasted until Early Oligocene (NP21); the latter defined by the contemporaneous presence of *Reticulofenestra bisecta* and *Sphenolithus moriformis* (Konstantopoulos, 2009). Studied sediments belongs to six different lithofacies (distal channel-fill deposits, proximal channel-fill deposits, interchannel deposits, levee deposits and slope fan deposits). The sedimentary model that best fits the depositional mechanisms and geometrical distribution of the turbidite units in Tritea basin is a mixed sand-mud submarine fan. The proximal and medial fan is represented by narrow channels, which cut muddy slope deposits and are flanked and covered by levees (Figure 4A). The distal fan is represented by amalgamated sandstone sheets and interlayered sandstone/mudstone sheets, which were formed at the mouth of the small channels (Figure 4B). The proximal sequences in Tritea basin comprises (1) a lower succession of aggradational and progradational units; (2) a locally thick, upward-fining, retrogradational, shale-dominated section in the middle; and (3) an upper section of typically mostly progradational and retrogradational units of thicker shales and sandstones. Progradational and aggradational units in the lower and upper divisions are interstratified with thinner retrogradational intervals. However, the proximal sequences are differentiated from the distal ones by having a higher proportion of thicker aggradational sandstones and thinner progradational units that contain a higher percentage of sandstone. The retrogradational units in the lower and upper divisions also contain a higher percentage of sandstone than those in the medial sequences but are of comparable thickness (Konstantopoulos and Zelilidis, 2012).

Hrisovitsi sub-basin

The total thickness of the studied succession is almost 350m (Figure 2B, 3B). Sandstone is restricted to channels, slumps, and to a lesser degree, levees, which contain only 30% sandstone. The transition from carbonatic to clastic sedimentation took place from Priabonian (Late Eocene)(NP18–NP20) (*sensu* Martini, 1971;

Berggren *et al.*, 1995), as indicated by nannofossil markers (*Ericsonia formosa*, *Reticulofenestra oamaruensis*, *R. bisecta*, *Coccolithus pelagicus*, *Cyclicargolithus floridanus*), and lasted until Early Oligocene (NP21), the latter defined by the contemporaneous presence of *Cyclicargolithus floridanus*, *Ericsonia formosa*, *Coccolithus pelagicus* and *Reticulofenestra hillae* (Konstantopoulos, 2009). Three different sedimentary facies were recognized: channel-fill deposits, levee deposits and interchannel deposits (Figure 5A, B). Hrisovitsi's turbidite system is characterized by small-scale channels filled by sandstone with sharp, irregular and sometimes erosional base, progressively decreasing downcurrent in grain-size and thickness of the sandstone strata which have laterally discontinuous geometries, and an increase in the proportion of the muddy strata. The channels are distinct and are characterized by fining and thinning-upward trends. Sedimentation took place in the upper parts of a submarine fan and represents the infill of a relatively deep, leveed channel, whereas the influence of the erosion during deposition was greater. This indicates more restricted basin topography in a position more proximal to the source area. Even the sandier beds have low thickness gradients both down flow and across flow, and become gradually mud-rich at their distal ends. Interchannel deposits are characterized by thin interbedding of sandstone and mudstone, produced by flows leaving the channel. The main body of the fan is characterized by the accumulation of amalgamated sheet turbidites separated by mudstone-prone units, with local development (Konstantopoulos and Zelilidis, 2012).

Finikounda sub-basin

Three major lithologies namely conglomerate, sandstone and mudstone were recognized. The total thickness of measured succession at Finikounda basin is approximately 420m thick, with almost continuous exposure (Figure 2C, 3C). The clastic sedimentation within the Finikounda basin started in Late Eocene times (NP17–NP18) (*sensu* Martini, 1971; Berggren *et al.*, 1995) as indicated by nannofossil markers (*Coccolithus pelagicus*, *Criboecentrum reticulatum*, *Cyclicargolithus floridanus*, *Ericsonia formosa*) and

Figure 4. A. Distal channel-fill, levee and channel margin deposits in inner fan. Thick-bedded sandstones, massive with normal grading. The sandstone to mudstone ratio ranging from 6:1 to 9:1 Sandstones show sharp and irregular bases. Beds with normal grading in the upper parts show parallel lamination and/or ripple cross-lamination. B. Outcrop of lobe deposits in outer fan. Note the thickening and coarsening upwards sedimentation cycles. This lobe package reaches 12m in thickness.

Figure 5. A. Outcrop of sandstones showing erosive bases. Note the passage from big to small-scale channels, interbedded with channel margin deposits. B. A slump horizon within levee deposits. Note the fine-scale interstratification of coarser and finer layers of sandstones and mudstones.

lasted until Early Oligocene times (NP21), the latter defined by the contemporaneous presence of *Reticulofenestra scrippsae*, *R. umbilica*, *Micrantholithus* spp., *Ericsonia formosa* (Konstantopoulos, 2009). In this case five different sedimentary facies were recognized: Slope deposits, channel-fill deposits, levee deposits, interchannel deposits and lobe deposits (Figure 6A, B). The submarine fan in Finikounda basin is characterized by the presence of distinct, small-scale, thickening-upward cycles, the lack of well-defined trends in bed thickness in the turbiditic succession whereas the proximal fan covers the distal fan. The lobes are well preserved, connected with the presence of attached lobes demonstrates the classification of the deep water deposits as a sand-rich submarine fan. This sand-rich, coarse-grained fan has a high net-to-gross percentage throughout. That percentage gradually decreases downdip, shows a gradual decrease in thickness and grain size downdip, and has excellent connectivity characteristics. This type of fan progrades gradually into the basin. The Finikounda sequence comprises three distinct stratigraphic

divisions: (1) a lower succession of two aggradational and two progradational units; (2) a typically thick, upward-thickening, aggradational, shale-dominated section in the middle; and (3) an upper section of typically two to four mostly progradational and aggradational units of thicker shales and sandstones. Erosionally based blocky, blocky-serrate, and upward-fining sandstone units are more common in the lower succession, whereas upward coarsening sandstone/shale units dominate the upper division. The style of fan initiation and progradation is strongly dependent upon the rate of relative sea-level fall. An abrupt fall in relative sea level drives rapid fan progradation with significant base-of-slope bypass and the development of a sharp fan base farther into the basin. In contrast, a steady fall in relative sea level is more likely to result in a protracted initiation of the fan system represented by transitional (coarsening- and thickening-upward) basal deposits. These features indicate a simultaneous interaction of progradation and aggradation for the submarine fan development (Konstantopoulos and Zelilidis, 2012).

Figure 6. A. Slope deposits overlying stacked channel system with channel-fill, levee and interchannel deposits. B. Outcrop of lobe deposits in outer fan. Note the thickening and coarsening upwards sedimentation cycle.

Paleoflow interpretation

The paleocurrent indicators that have been studied in the Tritea sub-basin show that the submarine fan system development was perpendicular to the westward progradation of the external Hellenides having a WNW trend (Figure 2A, 3A). Two minor palaeoflow directions were measured: one ESE trend and one NNW trend, in the southern parts of the basin and in upper stratigraphic parts of the succession. Also at two locations, in upper stratigraphic levels, which demonstrate the most distal part of the fan, a minor SSW direction occurs. The fact that this minor SSW axial palaeoflow direction was also found at this location, leads to the hypothesis that while most of the turbidity currents flowed perpendicular to the basin axis, some others were flowing axial to the basin axis, probably due to the presence of an intrabasinal high (e.g. the nowadays Skolis mountain), that restrict the basin width. As a result, the current pathways were not only westwards, from the Pindos thrust front, but switched laterally, suggesting a north to south direction. The presence of this axial direction shows a source point related to a deformed zone due to strike slip fault activity. This fault affects the basin development, and dictates current pathways which transfer sediment to the deeper parts of the foreland basin. Field observations on both the Gavrovo and the Ionian zones; reveal the existence of several minor strike slip faults that cut the thrust fault zones and strike at high angle to the main compressive structures. They are considered secondary features that arose during the thrust propagation to the west. Most of these faults correspond to ENE-WSW dextral and ESE-NNW sinistral strike slip faults.

Paleocurrent trends for the Hrisovitsi sub-basin indicate three directions: The major with NW perpendicular to thrust belts and two minor: the first with SSW axial to the Gavrovo and Pindos thrusts (Figure 2B, 3B) and the second one minor direction, in the lower stratigraphic parts of the unit, with a southward trend and radial pattern. The major NW trend occurs at the base of the stratigraphic column, related to the proximal part of the fan, whereas the minor SW trend is preserved at the upper part of the succession, responding to the distal turbidite deposits. The southward direction exhibited in the middle stratigraphic units reflects the passage from slope base to more distal fan zone.

Submarine fans in Finikounda sub-basin developed in two major directions, a SSE palaeoflow direction parallel to the basin axis, and a WSW direction perpendicular to Pindos thrust (Figure 2C, 3C). Moreover, at the base of the studied stratigraphic succession one SSE trend and one westward palaeoflow trend occurs whereas in the middle part of the column a WSW direction is preserved in three studied outcrops. Additionally, at the upper parts of the unit the palaeoflow trends are characterized by the presence of three minor directions, a SSW trend, a SSE and a southward. The presence of coarse-grained sediments in the northern and eastern margins of the basin combined with the palaeoflow trends indicates that the source material in the Finikounda sub-basin was derived both from the Pindos thrust front and from the northern ends of the basin.

Basin fills conditions and tectonic setting

The hypothesis proposed here links all the facies areas to an underfilled foreland basin system controlled by a hinterland-deeping thrust wedge. This interpretation is based on: the location of the Tritea, Hrisovitsi and Finikounda sub-basins, in the footwall of the

N-S Pindos and Gavrovo major thrusts; the division of the basin fill into three lithologic units, like Sinclair's model (1997), indicative of a foreland basin at an underfilled state; the basin setting between an eastern craton overlapped by the two first lithologic units and a northern thrust wedge overlapped by the third lithologic unit; the interfering of transverse and longitudinal turbiditic systems displaying a growth stratal pattern in the West Peloponnese area; the identification of depositional areas included in a foreland basin system (DeCelles and Giles, 1996).

A qualitative model for the forebulge migration and stratigraphic fill of an underfilled foreland basin during the early underfilled period and late underfilled period is proposed for the Pindos foreland basin. During the early underfilled period, flexural subsidence is created in the region (Tritea sub-basin in the north, Finikounda sub-basin in the south) proximal to the Pindos mountain belt due to loading by emplaced thrust sheets. The foredeep zone receives relatively limited sediment supply from the Pindos mountain system and the basin is in an underfilled condition.

During the late underfilled period, shift of subsidence centre from the region (Hrisovitsi sub-basin in the centre) proximal to the Pindos thrust belt gradually to the distal foredeep zone result in the rapid regression of the shoreline on the proximal Pindos foreland basin and the cratonward migration of the forebulge and back bulge zones. Continuous cratonward migration of the new forebulge results in gradual erosion and reworking of the previously deposited back bulge strata, forming a diachronic erosion surface in the central part of the basin, mostly in Hrisovitsi sub-basin.

At the end of the underfilled period, the whole foreland basin is characterized by a relatively flat topography (Hrisovitsi and Finikounda sub-basins) and the forebulge zone is uplifted locally and sandstones are deposited along the flank of the uplifted and uplifting forebulge zone (Tritea sub-basin). It is proposed that cratonward migration of the sediment loading centre results in the rapid cratonward migration of the forebulge zone during the late underfilled period.

Two successive thrust episodes distinguished in the evolution of the Pindos foreland basin. The first thrust episode developed during late Eocene times. It was associated with a foreland basin system always maintained at an underfilled state. The thrusting resulted in a hinterland-dipping wedge which grew by thrusting within the wedge interior. The second thrust episode developed during early Oligocene times. It was associated with a foreland basin system which evolved from underfilled to filled and bypassed stages. During the early underfilled period, the basin style is mainly controlled by the orogenic loading, and a prominent forebulge zone with an approximately fixed location is formed. During the late underfilled period, the basin style is mainly controlled by the sediment loading, and the forebulge zone move very fast along with the rapid cratonward shift of the sediment loading center.

We neglected the critical importance of the sediment loading in influencing the basin style during the late underfilled period, and simply correlated orogenic loading and unloading periods with an underfilled basin and an overfilled basin, respectively. However, over a longer time period and between different tectonically-driven cycles, the orogenic loading plays a more important role than the sediment loading for the migration of the forebulge zone. When a new tectonically-driven cycle begins, driven by the renewed intense thrusting, generally the deformation front advances basinwards compared with the previous thrusting event. This association of an underfilled foreland basin and a hinterland-dipping thrust wedge can

be interpreted as illustrative of the initial stages of thrust-wedge growth controlled by continental subduction processes in deep marine environments.

Underfilled foreland basin

During Late Eocene, slope (channel-fill and levee deposits) and outer fan (lobes, inter-lobes and lobe-fringe deposits) sediments were deposited. Tritea sub-basin is characterized mainly by the deposition of inner and outer fan deposits, while in the central part of the Peloponnese peninsula, in Hrisovitsi sub-basin, slope and inner fan deposits were developed (Figure 7A, B). During this time in Finikounda sub-basin, slope and outer fan deposits were deposited over fan-delta deposits (Figure 7C). Pindos foreland basin in this time interval, in the Tritea sub-basin (north), seems to have been broad and deep, whereas in the central part in Hrisovitsi sub-basin, the

foreland was more restricted spatially. Finikounda sub-basin, in the south, is restricted and shallower to the north but of broad and deep to the south. The major entry point of sediments in the Tritea sub-basin was restricted mainly by the thrust front whereas in the northern and southern margins seems to be fed by a minor feeder system. In Hrisovitsi the feed of the sub-basin was made by isolated major channels and canyons. Finikounda sub-basin was fed by two major entry points, one in to the north and one coming through the thrust front. The palaeocurrent patterns characterizing the above-described basin configuration consist of one main phase, near the entrance points where the flows are directing perpendicular to the basin axis.

During the Early Oligocene Tritea sub-basin is characterized mainly by the deposition of slope and outer fan deposits, Hrisovitsi sub-basin by inner and middle fan deposits, whereas Finikounda sub-basin, by inner and outer fan deposits (channel-fill and levee deposits were deposited synchronously with lobes, inter-lobes and lobe-fringe

Figure 7. Generalized model diagram for each one of the three studied sub-basins modeling the flow regime that was recognized in Pindos foreland basin, controlled by the presence of strike-slip faults, intrabasin highs and internal thrusting tectonic activity.

deposits). In this time interval, Pindos foreland basin in Peloponnese peninsula, in Tritea sub-basin (north) seems to be narrower and shallower, in the northern margins becomes broad, whereas in the same time, in the central part, in Hrisovitsi sub-basin, the foreland basin continues to be restricted. In the south, Finikounda sub-basin was already restricted, and becomes more narrow, but continues being deep to the south. Tritea sub-basin was now fed by two major entry points, by the thrust front and a major feeder system in the north. The majority of sediments in Hrisovitsi sub-basin were derived from the northern parts of Pindos thrust. Finikounda sub-basin seems to have been continuously fed by a major entry point in the north and a minor one coming through the thrust front.

The presence of an intrabasinal high in Tritea sub-basin influenced the paleocurrent network, as the paleocurrent directions turns parallel to the basin and intrabasinal high axis (Konstantopoulos and Zelilidis, 2012). The presence of transfer faults that cross-cut the high results in the formation of low relief areas that act as pathways for the transportation of sediments over long distances (Kamberis *et al.*, 2000; Zelilidis *et al.*, 2008). In the Finikounda basin, due to the presence of internal thrusting, an intrabasinal high was formed (Konstantopoulos, 2009). This high influenced the thickness and the geometry of the accumulated sediments. Intrabasinal high as referred for the northern part of Pindos foreland basin formed due to internal thrusts (Gavrovo, Internal Ionian, and Middle Ionian) activity (Avramidis *et al.*, 2002). The activity of internal thrusts is related with the westwards migration of Hellenides. There is a gradually reduce of thrust activity to the east with a consequence increase of thrust activity to the west. So, at first stages, foreland basin changed from a simple-type to a split into minor-type basins (according to Ricci-Lucchi, 1986). Finally, at time when only the Ionian thrust was active during Late Miocene-Early Pliocene the foreland basin changed to a piggy-back basin. This scenario could explain the foreland's gradual change from broad to restrict.

Paleocurrent data (NW, SW) support that the source area for the Pindos foreland clastics appears to be in the southeast and northeast. Most of the sandstones are lithic arkoses and feldspathic litharenites. These types of sandstones show that the rate of erosion must have greatly overbalanced the rate of chemical decomposition (Folk, 1974), whereas require rapid deposition in order to preserve unstable

fragments from abrasion. It requires more rapid detrital influx due to active tectonism and high relief. Tectonic uplift seems to be an essential factor in producing the rapid erosion needed to form these sandstones. Climatic factors (arid to too cold) play a less important role. The presence of minor amounts of rounded quartz, cherts and resistant heavy minerals suggests a minor distribution of reworked terrigenous sediments. Rock fragments of all kinds (but mostly chert) have a strong correlation with grain size.

The geochemistry and the petrography of the studied sediments also support the preserved basin-fill conditions. The dominance of the active continental margin (ACM) and continental island arc (CIA) with a very limited passive margin (PM) extent geochemical signature corresponds to the abundance of lithic fragments as common constituents in the studied sandstones and mudstones. The application of various discriminant schemes based on major, trace and rare earth elements, suggests that the Pindos foreland basin sandstones were deposited in an active continental margin environment, where the source area was mostly of mafic/ultramafic and less felsic composition (Konstantopoulos and Zelilidis, 2011b).

Based on our results of the provenance analysis we therefore conclude a forearc basin in front of an evolving oceanic to continental arc (Figure 8). The above conclusions integrated with sedimentological data, (e.g. palaeocurrents) suggest that the study area was served as a forearc basin, of the 'contracted' type. The North Pindos foreland basin in Peloponnese peninsula (Tritea sub-basin) have significant contribution of arc-like source areas and are probably also affected by matter from oceanic within-plate sources delivered into the trench by subducting processes. In contrast the South Pindos foreland basin (Hrisovitsi and Finikounda sub-basins) are dominated by an active continental margin setting with minor contributions from magmatic source areas. Since those clear evidences that were found in the data presented here, we can speculate that this is due to infiltration of material through temporarily connected narrow pathways to an arc.

Our results clearly assist the hypothesis of the transition to an active and passive margin setting towards the west. The preservation of detrital material of plutonic, volcanic, sedimentary and metamorphic origin in the same strata is indicative of only a minor weathering and sorting influence acting on the detritus on its way from the sediment

source to the depositional basin (Konstantopoulos and Zelilidis, 2011b). In turn, this implies (1) relatively short transport paths and thus potentially marked relief; and (2) only minor intermediate storage of sediment. These features are typical of tectonically active basins at active continental margins or of strike-slip basins. The most reasonable geotectonic setting that accommodates all these sediment sources is continental basins formed in the back-arc region, i.e. back-arc, strike-slip and foreland basins. A continental island arc is by definition an 'island arc formed on well-developed continental crust or on thin continental margin' with a provenance of a 'dissected magmatic arc-recycled orogen'. The latter observation confirms the

Figure 8. A proposed geodynamic model represents the setting of the Pindos foreland basin in Peloponnese peninsula during the late Eocene- early Oligocene time.

agreement between petrographical and geochemical results, regarding the tectonic setting of the sedimentary basin. More detailed and advanced geodynamic and structural discussions about the geodynamical development of the Pindos foreland basin in W. Peloponnesus region should be presented elsewhere.

Conclusions

The Pindos foreland basin, in Peloponnesus area, from the late Eocene to the early Oligocene was an underfilled basin which received sediment from both the thrust front and the peripheral bulge. The underlying thrust wedge displayed a top surface which descended toward submarine internal zones. Thus, such a wedge can be compared to the hinterland-dipping wedges which were stated to be transported down by subduction processes while they were forming. This association of an underfilled foreland basin and a hinterland-dipping thrust wedge can be interpreted as illustrative of the initial stages of thrust-wedge growth controlled by continental subduction processes in deep marine environments. The proximal and the distal part of the Pindos foredeep indicated by the distribution of the grain size in Ionian and Gavrovo zones turbidite deposits and suggest a multiple feeder system. The feeder system for the Pindos foredeep can be described by a major entry point and by minor canyons and channels as paleocurrent interpretation showed. The widespread subtle topographic uplifts and erosion surfaces in a foreland basin were produced by continuous cratonward migration of forebulge zones during underfilled periods. During this underfilled period, flexural subsidence is created in the region proximal to the mountain belt due to loading by emplaced thrust sheets. The foredeep zone receives relatively limited sediment supply from the mountain system and the basin is in an underfilled condition.

Due to the presence of internal thrust faults in the three studied sub-basins, directing parallel to the basin axis and to the master bounding faults, at least two intrabasinal highs were formed (Tritea and Finikounda sub-basins). The continuity of these highs was interrupted by strike-slip faults, which controlled the formation of these sub-basins. The presence of these strike-slip faults that crosscut the highs results in the formation of low relief areas that act as pathways for the transportation of sediments in long distances. It appears that the strike-slip fault network developed by a sheared joint-based mechanism is responsible for the apparent conjugate fault sets composed of the right- and left-lateral faults. Based on field relationships, it is likely that strike-slip faulting and thrust faulting were active simultaneously, although thrust faulting and folding appear to have initiated first. Having both types of faults active at the same time is consistent with the predominant E-W compression that is the mutual driving force, as well as with mechanical models of folded layers. This co-activity continued to at least the Oligocene times.

This case study may illustrate a predictable association of facies for the underfilled phase of any forearc foreland system in which accommodation is controlled by both orogenic and sublithospheric loading.

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