Global and Planetary Change 103 (2013) 207–231

Contents lists available at SciVerse ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Stages of sedimentary prism development on a convergent margin — Eocene Tyee Forearc Basin, Coast Range, Oregon, USA

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ARTICLE INFO

Article history:
Accepted 15 November 2012
Available online 24 November 2012

Keywords:
Tyee Basin
forearc
sedimentary prism
slope channel
slope apron
deep-water fan
basin-margin clinoform

ABSTRACT

Architecture of ancient forearc basin successions can be difficult to reconstruct because of the widespread syn-depositional and post-depositional deformations experienced by many forearc basin-fills. For this reason various techniques have been used for reconstructing forearc basin-infill geometry, including geochemical correlation. The Tyee Basin succession exposed in Coast Range of Western Oregon, USA, is an Eocene forearc-fill that includes genetically related non-marine, shallow marine and deepwater clastic deposits and is gently deformed. Reconstruction of the depositional geometry of the Tyee Basin succession from detailed outcrop and subsurface data reveals two distinct stages of development for this active basin-margin. These stages are characterized by two different basin-margin clinoform architectures and also by a pronounced change in the character of the associated deepwater deposits. During the initial stage, the basin-margin clinoforms are smaller (<250 m clinoform height) and strongly progradational, with clinoform topset dominated by fluvial deposits. At this stage thick sand-rich unconfined turbidite beds accumulated on the slope segment of the clinoforms and extended out onto the basin-floor. Large scale slope conduits such as slope channels or canyons, are notably absent in this stage. The second stage is characterized by larger clinoform height (>500 m), a greater degree of topset aggradation with repeated fluvio-deltaic cycles on the shelf, and well-organized, large turbidite channels on the slope. The turbidite channels supplied medium-grained sands to the extensive, stacked basin-floor fans. The first stage described above marks the early development of a shelf-slope prism on the Tyee continental margin, and has been interpreted by some earlier workers as an unique category of basin-margin architecture, termed as a 'submarine ramp'. However, this was only the initial stage of development of the Tyee margin and it was followed by a period of basin-filling when repeated fluvial and shallow marine shelf-transit cycles fed well-organized turbidite channels on the slope as well as Tyee Basin floor fans. The large volume of sediment deposited during the initial stage, resulted from of the unique geometry of the Tyee Basin, as influenced by the presence of pre-existing topography on the accreted oceanic basement underlying the Tyee succession.

1. Introduction

Because of the subsequent (post-depositional) tectonic deformation of forearc basin deposits, there are only a limited number of studies that describe large-scale depositional architecture of such basins in ancient successions (Tokuhashi, 1989; Takashima et al., 2004; Trop, 2008). In some cases, seismic data can provide a basis for basin-wide correlation (e.g., Marcaillou and Collot, 2008), but are of limited use in detailed identification of depositional environments. As a consequence, the well-known clinoformal geometry (Johannessen and Steel, 2005; Helland-Hansen et al., 2012) of the shelf-slope sedimentary prism (alternatively termed as the 'basin-margin sediment wedge' as described by Burgess and Steel, 2008) that include non-marine to shelfal topset and a deep-water slope foreset, cannot be easily demonstrated from many ancient forearc margins. The Tyee Forearc Basin in the Coast Range of Oregon (Fig. 1) was filled in Early to Middle Eocene and was gently deformed subsequently, so that a reconstruction of the clinoformal geometry of the shelf-slope sedimentary prism at the Tyee forearc margin can be attempted, using outcrop and subsurface data. The exposed deposits of the Tyee Forearc Basin include non-marine, shallow marine and deepwater deposits, which can be interpreted as various components of the proposed basin-margin clinothems, provided their chrostratigraphic equivalence is established by basin-scale correlation. This article puts forward a depositional model for the clastic succession of the Tyee Forearc Basin, primarily on the basis of outcrop observations, that allows reconstruction of the clinoform geometry, and demonstrates the stages of basin-margin sediment wedge development at this active forearc margin. The Tyee Basin is thought to have had topographic/bathymetric variations as a result of pre-existing basement structures (Snavely and Wagner, 1963). The proposed depositional model also demonstrates the effect of bathymetric variation on

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0921-8181/$ – see front matter
http://dx.doi.org/10.1016/j.gloplacha.2012.11.006

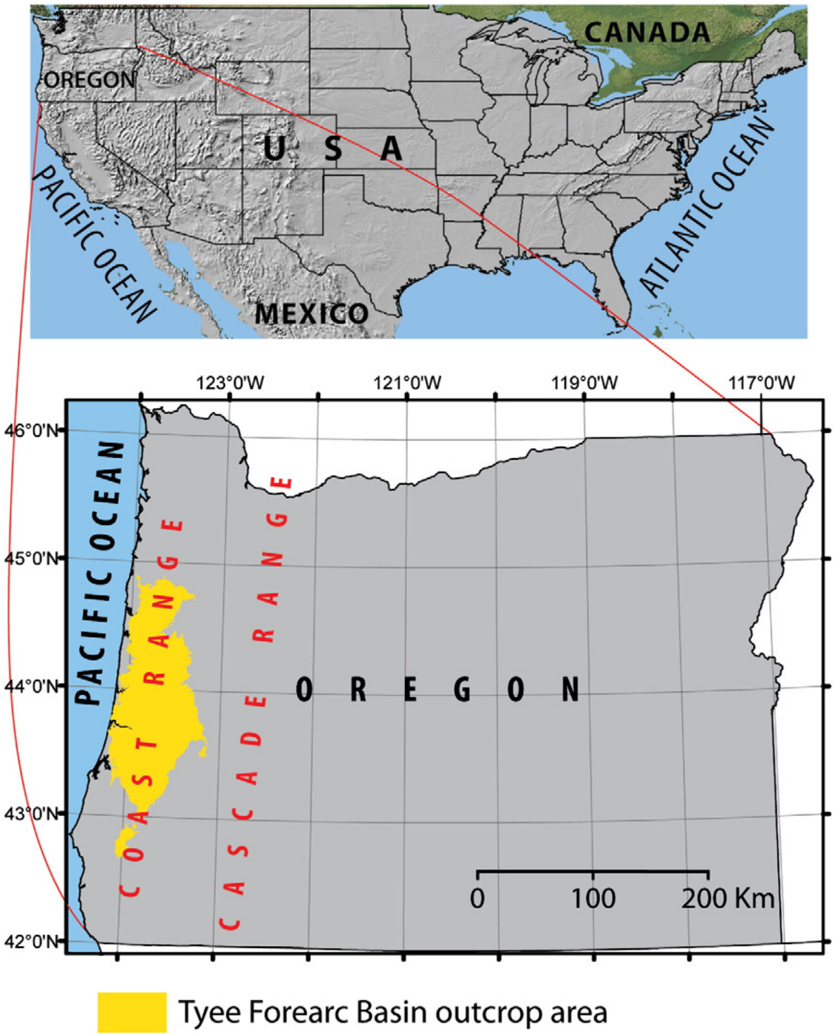


Fig. 1. Location of Tyee Forearc Basin outcrop area in Coast Range, western Oregon — the Cascade Range (volcanic arc) lies to the east of Coast Range.

basin-margin clinoform height, clinoform progradation direction and shelf-edge trajectory (a measure for relative importance of progradation of shelf-edge versus aggradation on the clinoform topset, e.g., Carvajal and Steel, 2006).

The fluvial to coastal, shallow marine and deepwater deposits of Tyee Forearc Basin were previously believed to be a near-continuous, axial fill succession, with the basin-axis running sub-parallel to the N–S tectonic grain of the convergent margin. In addition, the Tyee Forearc Basin was the type area for the development of "submarine ramp" model for such basin margins (Heller and Dickinson, 1985), built as an alternative to a previous fluvial-to-slope-to-fan model for the Tyee Forearc Basin (Chan and Dott, 1983) (Fig. 2). These two contrasting depositional models for the Tyee Forearc Basin infill, however, have some common features, including — (1) a narrow to missing shelf and a direct linkage of the fluvial deposits to slope and deepwater deposits; and (2) sediment input to the basin by multiple rivers, effectively behaving as a line source, and sand supply to the basin floor controlled by multiple sediment conduits on the slope.

A new depositional model for the Tyee Forearc Basin is advocated whereby most sediment was input in a transverse (SE to NW) manner before the deepwater turbiditic system swung longitudinally with the tectonic grain, and where there was clear clinoformal outbuilding of a shelf to deepwater slope system with numerous large-scale submarine channel systems for much of the time interval during which the basin was filled. Two main stages of development are documented for the Tyee Forearc Basin infilling — (1) a proto-shelf stage, steeper and narrower than normal, that developed along the early basin margin, characterized by the absence of large sediment bypass conduits on the slope (morphologically similar to the "deepwater ramp" margin model as described by Heller and Dickinson, 1985); and (2) a mature shelf stage, wide shelf to slope system that is common to most plate-margin basins worldwide (distinct alluvial to shelf segment, shelf-edge, well-developed deepwater slope segment with major turbidite channels supplying sediment to the basin floor).

The distribution of various lithofacies within the Tyee Forearc Basin and the paleo-current information indicate that pre-existing basin topography played a significant role in shaping the overall geometry of the basin-fill. Otherwise we suggest that the basin evolved in a fairly normal manner, with rivers and deltas repeatedly transiting a gradually widening shelf, with huge volumes of sand and mud being delivered periodically across the shelf edge, initially in sheets and later into spectacular turbidite channel systems that led out into large and thick basin-floor fan systems.

2. Geological background

The Paleogene sedimentary succession of the Coast Range of Oregon overlies an oceanic basement known as the Siletz River Volcanics. The Paleogene sedimentary succession includes Paleocene to Early Eocene Umpqua Group, Early Eocene Tyee Formation, and late Early Eocene to

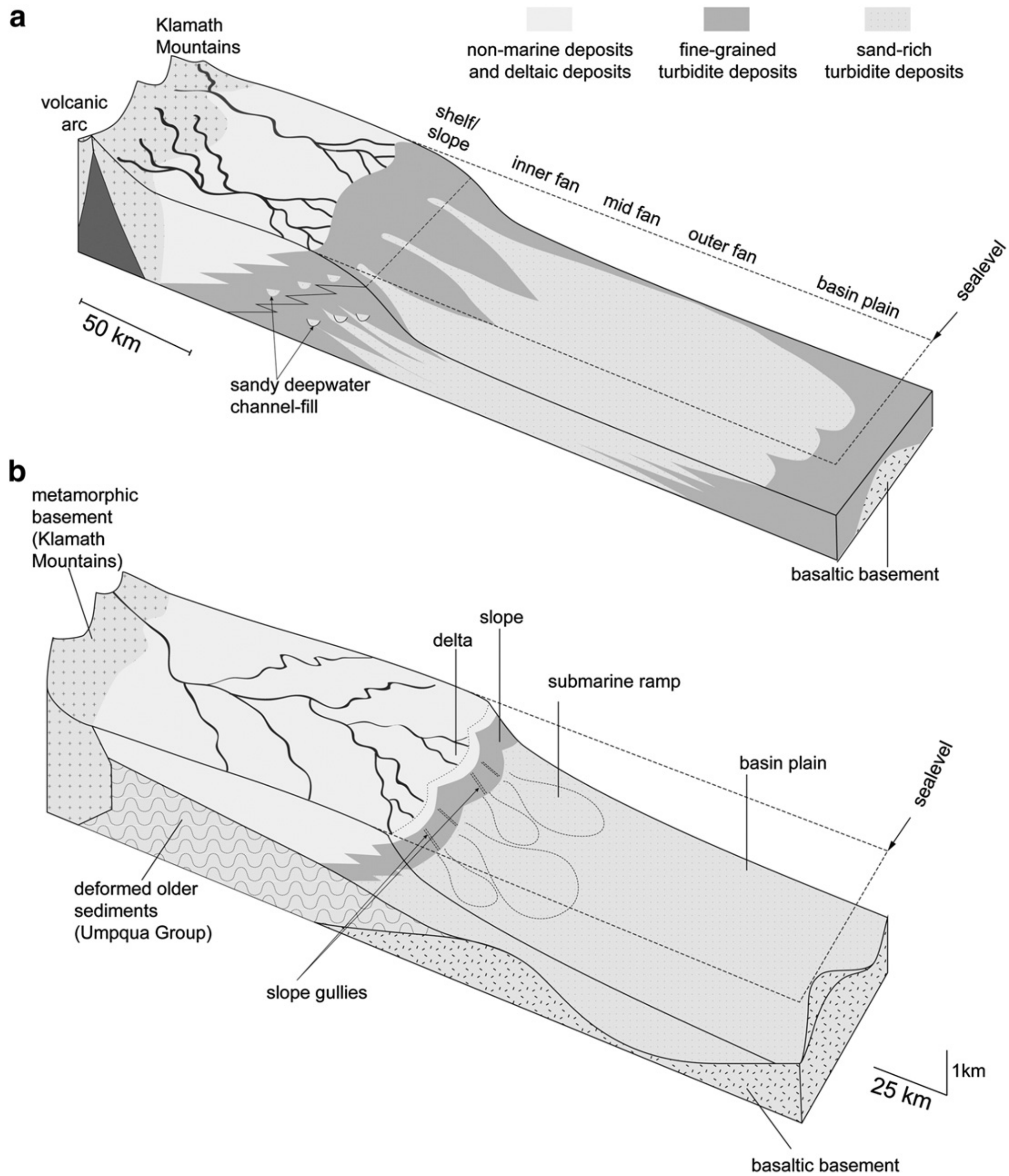


Fig. 2. Pre-existing depositional models for Tyee Forearc Basin. a. 'Fan model' for deep water deposits of Tyee Forearc Basin showing multiple fluvial feeders, relatively narrow shelf-slope segment with deltas close to the shelf-edge and multiple slope channels on lower slope, and sand-rich deepwater fan deposits including inner fan, mid-fan and outer fan facies (after Chan and Dott, 1983). b. Submarine ramp model for Tyee Forearc Basin — showing deformed older (pre-Tyee Forearc) sediments, undeformed younger Tyee Forearc sediments (Heller and Dickinson, 1985).

Middle Eocene Elkton, Bateman and Spencer Formations. The Umpqua Group is composed of shallow to deepwater clastic sediments that were deposited prior to the formation of Tyee Forearc basin and have a different tectonic history. The overlying sedimentary succession of the Tyee Forearc Basin includes the Tyee, Elkton and Bateman Formations. The Paleogene sedimentary succession is bounded to the south by the Mesozoic Klamath Mountains and to the east by overlying volcanics of the Cascade Range (Ryu, 2003). An east–north-east trending basement high of Siletz River volcanics known as the Umpqua Arch has been identified in southern part of Coast Range by geophysical studies. Strongly deformed Umpqua Group strata crop out in areas south of Umpqua Arch. Gently deformed rocks of the Tyee Forearc Basin unconformably overlie the Umpqua Group strata and are exposed over an area of nearly 15,000 km^2 in the Coast Range in a N–S trending outcrop belt. Younger Coos Bay Basin deposits (Late Eocene) are exposed on the coast west of southern Coast Range near the town of Coos Bay.

2.1. Tectonics of the Tyee Forearc Basin

The Early to Middle Eocene Tyee Forearc Basin can be related to Farallon/Kula plate subduction under the North American Plate (Simpson and Cox, 1977; Duncan, 1982; Heller and Ryberg, 1983; Wells et al., 2000). The pre-tertiary, metamorphosed Klamath Mountains represent the continental block; the volcanic arc was located along present-day central Oregon, whereas the corresponding deepwater trench was located below the present-day outer shelf of the Pacific continental margin of Oregon (Fig. 3a). The basement under the Coast Range (Siletz River Volcanics), which is a thick succession of Paleocene and Early Eocene alkalic and tholeiitic pillow lavas and submarine breccias is thought to represent an oceanic plateau, island chain or marginal basin that was accreted onto the continent in the Early Eocene (Wells et al., 2000). The prevailing theory about the origin of this oceanic terrane (known as the Siletz River Volcanic Terrane) attributes it to

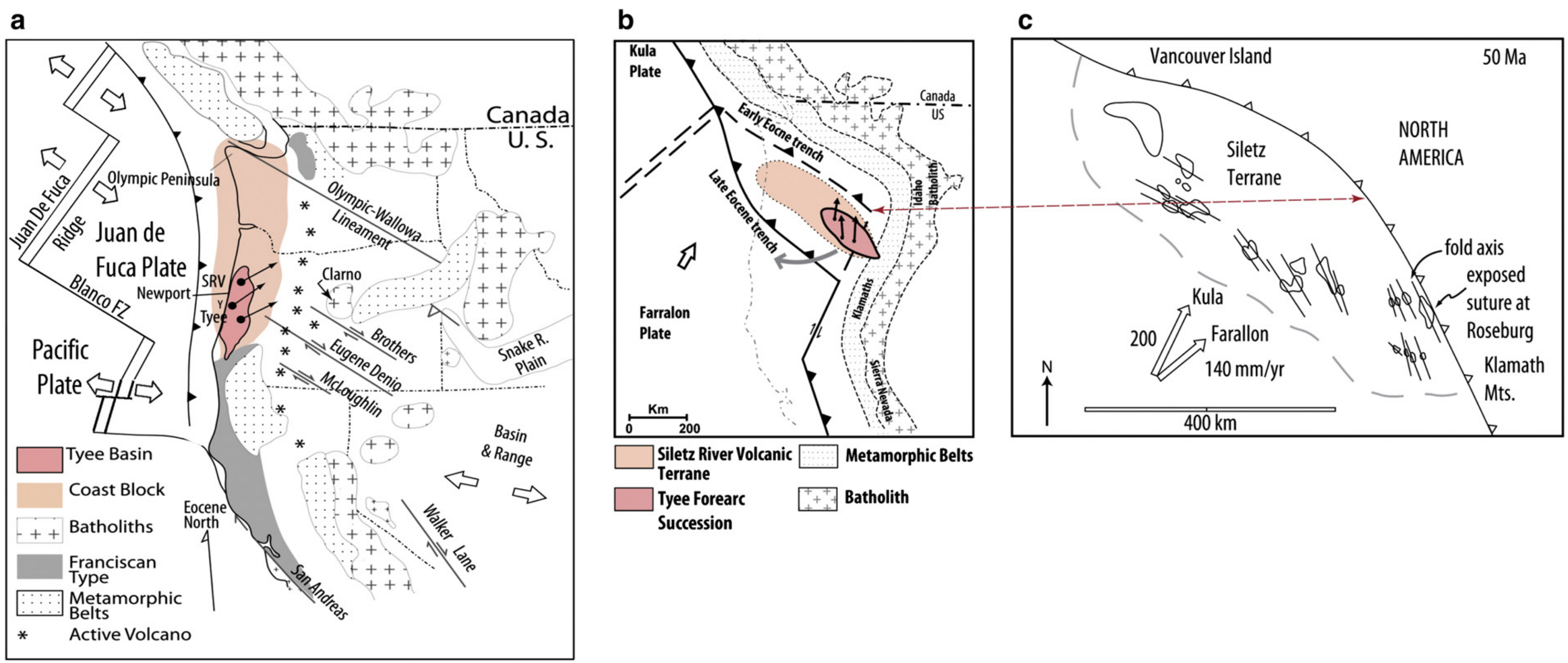


Fig. 3. Some important tectonic elements of the present-day western North America and a model for accretion and post-Early Eocene rotation of Siletz River Volcanics (SRV). a. Important tectonic elements of western North America in relation to the present-day orientation of the Tyee Basin and it's volcanic basement (Coast Block), outcrop area of the relative undeformed clastic sediments of Tyee Basin is marked; note, the orientation of recorded magnetic field direction from Paleocene/Early Eocene volcanics indicated by black arrows suggesting post-Early Eocene Rotation of more than 65°. b. Model for accretion and rotation of the Siletz River Volcanics (SRV), showing possible tectonic configuration of the volcanic terrane, which was accreted on to North American plate in Early Eocene (~50 Ma) following an arrest in subduction along an Early Eocene subduction zone, post-Early Eocene rotation clockwise rotation occurred around a pivot point near the northern end of the accreted terrane (the black arrows indicate possible original orientation of the magnetic field). c. Possible orientation of the suture zone in Early Eocene (~50 Ma) (after Wells et al., 2000).

the collision and accretion of a hotspot generated oceanic island chain or an oceanic plateau to the North American continental block following an arrested subduction (Simpson and Cox, 1977; Heller and Ryberg, 1983). Paleomagnetic data from the Coast Range of Oregon strongly suggest that the Siletz River Volcanic Terrane along with the overlying Eocene sediments of Umpqua and Tyee Forearc basins experienced a clockwise rotation of more than 65° since late Early Eocene time (Simpson and Cox, 1977; Heller and Ryberg, 1983). The tectonic model for this rotation (Fig. 3b) also incorporates the idea that the suture zone between Siletz River Volcanic Terrane and North American continental plate represents an early Tertiary subduction zone that was clogged because of the presence of a possible hotspot-generated aseismic ridge or a series of oceanic islands/seamounts (Simpson and Cox, 1977). As a result, a new subduction zone formed farther seaward in late Early Eocene. Observations from several data sources supports this model, including observation made by Heller and Ryberg (1983) from petrology and composition of Umpqua and Tyee Forearc Basin sandstones and interpretation of offshore seismic lines by Snavely et al. (1980) (Snavely et al., 1980). Wells et al. (2000) have presented a possible configuration of the suture zone representing the eastern boundary of Siletz Terrane (also the possible Early Eocene Trench) extending along Wild Life Safari Fault near Roseburg in Oregon to Vancouver Island in the north (Fig. 3c).

Heller and Ryberg (1983) presented a depo-tectonic model for the Tyee Forearc Succession (Fig. 4a,b). A generalized depo-tectonic history for the entire Paleogene succession of Coast Range of Oregon, by Wells et al. (2000), states that the Siletz River Volcanics probably represent oceanic crust formed on seamounts or oceanic islands that was subducting under the North American Plate while the overlying shallow to deep marine sediments were deformed by westward verging imbricate thrust faults (Ryu, 2003). The sediments accumulating at that time represent the lower part of pre-Tyee Umpqua Group. Subsequently, subduction along the Early Eocene trench ceased, probably as a result of clogging due to the buoyant nature of the seamount terrane (Ryu and Niem, 1999). Shallow marine sandstones and deepwater turbidites of the uppermost pre-Tyee Umpqua Group were deposited at this stage. A new subduction zone formed approximately at the location of present-day outer shelf off Oregon Coast, and a magmatic arc formed in central Oregon. Subsidence of the area between the magmatic arc and the subduction zone to the west resulted in development of the Tyee Forearc Basin, which received sediment between late Early Eocene and Middle Eocene times.

2.2. Stratigraphy of Tyee Forearc Basin

Table 1 summarizes the various stratigraphic columns for the Paleocene to Middle Eocene succession of Coast Range of Oregon proposed by previous workers. The latest stratigraphic column as proposed by Ryu & Niem, and Ryu, Wells et al. (2000) subdivides the Coast Range Paleogene sedimentary succession, that overlies the Siletz River Volcanics, into (1) Bushnell Rock Formation and Slater Creek member; (2) Tenmile Formation; (3) White Tail Ridge Formation; (4) Camas Valley Formation; (5) Tyee formation with Tyee Mountain, Hubbard Creek and Baughman members; (6) Elkton Formation (and laterally equivalent Lorane Shale); and (7) Bateman and Spencer Formations (Ryu et al., 1992). Units 1–4 constitute the pre-Tyee Umpqua Group (Table 1) and are recognizable in the southern Coast Range. In the northern Coast Range (north of Umpqua Arch) these units are not easily identifiable and the deepwater clastics of equivalent age have been termed as Undifferentiated Umpqua Group. The Bushnell Rock Formation is composed of shallow marine to deepwater clastics with notable conglomeratic facies, and it party interfingers with the basaltic basement. The overlying Tenmile Formation is a complex deepwater fan succession composed of turbidite sandstones and mudstones (Wells et al., 2000). The shallow marine and continental deposits of the White Tail Ridge Formation unconformably overlie the Tenmile Formation. The uppermost formation of the pre-Tyee Umpqua Group is the Camas valley Formation which is composed of fine grained clastics, probably deposited in deepwater environment. It is important to note that the shallow marine and continental deposits within the Umpqua Group are restricted to the southern part of the Coast range south of the Umpqua Arch. To the north of the Umpqua Arch, the Umpqua Group is represented by predominantly fine-grained deepwater deposits.

Biostratigraphic data show that the Tyee Formation is of late Early Eocene (Ulatisian) age (Bukry and Snavely, 1988). Ryu et al. (1992) discussed the age, contact relationships and detailed subdivision of stratigraphic units within the Tyee Forearc Basin strata — the Tyee Formation, the Elkton Formation and the Bateman Formation. Ryu et al. (1992) subdivided the Tyee Formation into three members

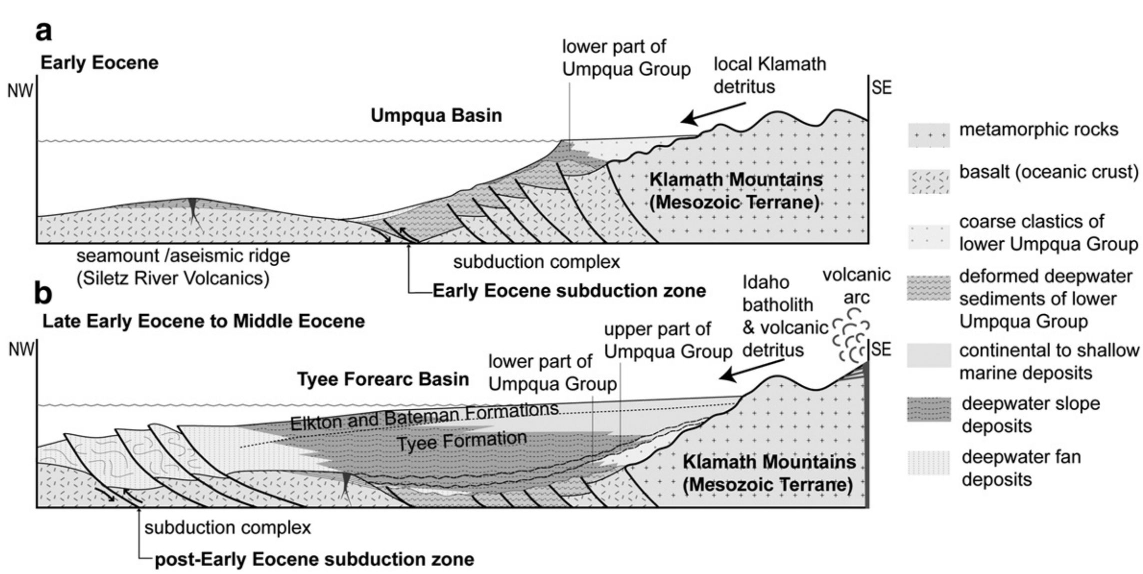
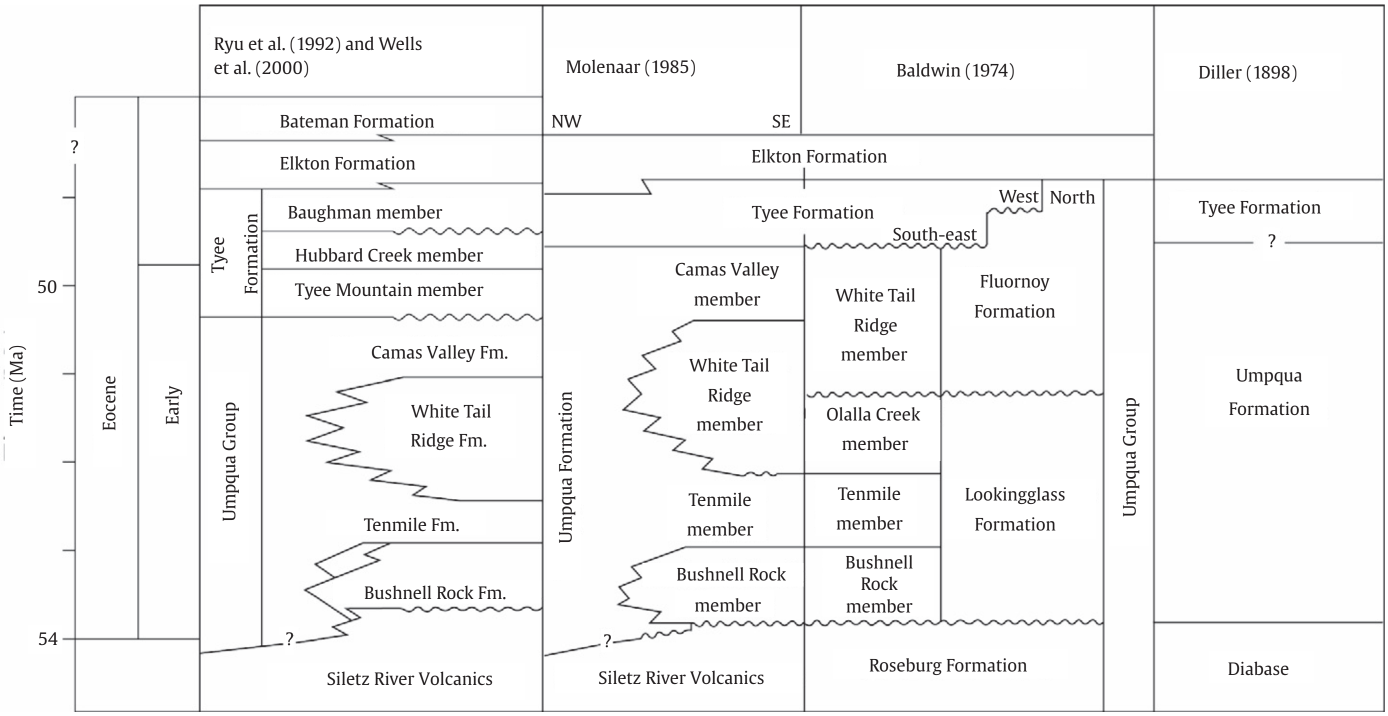


Fig. 4. Depo-tectonic model for the Tyee forearc Basin. a. Early Eocene subduction and deposition of the Umpqua Group. b. Arresting of subduction along early Eocene trench and formation of a new subduction zone in late Early Eocene resulting in accretion of the Siletz Terrane followed by late early Eocene to middle Eocene forearc sedimentation (modified from Heller and Ryberg, 1983).

Table 1
Stratigraphic units of Paleogene succession of the Coast Range of Oregon including the sedimentary succession of the Tyee Forearc Basin — a comparison of the latest stratigraphic scheme (proposed by Ryu et al., 1992) with several stratigraphic schemes proposed in the past (modified from Wells et al., 2000).



which are the basin-floor fan component, the slope component and the fluvial-deltaic component of the Tyee Formation respectively. Ryu et al. (1992) assigned the deepwater fan deposits of the Tyee Forearc Basin to the Tyee Mountain member that consists of very thickly bedded, amalgamated micaceous sandstones and mudstones. The contact between Tyee Mountain member and the underlying Camas valley Formation (of Umpqua Group) is a disconformity (Ryu et al., 1992). The deepwater slope deposits of Tyee Formation, including muddy and sandy turbidite deposits, were assigned to the Hubbard Creek member. Ryu et al. (1992) placed this unit above the Tyee Mountain member. Hubbard Creek member consists predominantly of well-laminated micaceous, bathyal foraminifer-bearing mudstones and siltstones containing spectacular nested turbidite channels as well as sheetlike, thin- to thick-bedded turbidite sandstones. Ryu et al. (1992) assigned the fluvial, shallow marine and shoreline deposits of Tyee Formation to the Baughman member and placed them above Hubbard creek member, recognizing partial interfingering between these two units. The Baughman member consists of thick bedded, often cross-stratified, micaceous lithic–arkosic sandstones and mudstones, with marine trace fossils in some localities. Fine-grained slope deposits (siltstone–mudstone) with nested, thick turbiditic slope-channel sandstones (micaceous arkosic sandstone) of central part of Tyee Forearc Basin outcrop area have been assigned to Elkton Formation. The Elkton Formation has been defined as a unit that conformably overlies and partially interfingers with Baughman member of Tyee Formation. A thick, predominantly sandy deltaic succession, exposed in a topographically high area in central Tyee Forearc Basin (south of Umpqua River Valley), was named the Bateman Formation. Ryu et al. (1992) interpreted these sandstones as conformably overlying and interfingering with Elkton Formation. The stratigraphic subdivisions of the Tyee forearc deposits, as listed above, are part of a lithostratigraphic classification scheme as is evident from the fact that the deepwater fan deposits, the slope deposits and the fluvio-deltaic deposits have been placed in separate stratigraphic units. In the present work we use this stratigraphic nomenclature without implying any chronostratigraphic significance to the unit boundaries and henceforth refer to the Tyee Formation, Elkton Formation and the Bateman Formation together as the *Tyee Forearc Succession*.

3. Data and methods

The Tyee Forearc Succession is exposed over an area of 15,000 km^2 in southern coastal Oregon within the geographical area known as the Coast Range. The Tyee sandstones and siltstones are well-exposed along a series of river valleys and major road cuts, which allowed the reconstruction of several dip and strike-oriented cross sections built from numerous small outcrops. About 1200 outcrops (Fig. 5a) were measured and studied in detail for grain-size, sedimentary structure, biogenic structures, bed thickness and bed orientation. On the basis of these observations a number of broad lithofacies types were identified and they were grouped into several lithofacies associations. The lithofacies associations were assigned to a range of depositional environments from non-marine to deepwater. Using the outcrop information including bed orientation data, the major lithofacies boundaries were mapped across most of the Tyee Forearc Basin. Measurements from five petroleum exploration wells drilled in the Coast Range that penetrate parts of the Tyee Forearc Succession and the underlying Paleocene–Early Eocene sediments (Fig. 5a,b), were of the only subsurface data used for this study. The subsurface data (wire-line log data and mud logs from these wells) are not adequate to independently establish a basin-wide correlation. Nonetheless, the well logs have been useful in studying grain-size trends within the study interval, which was used in interpretation of depositional environments (Fig. 5b). A basin-wide stratigraphic correlation of the well data has also been attempted using standard petroleum industry software. However, extremely high well spacing resulted in high degree of uncertainty, which was minimized by the incorporation of closely spaced

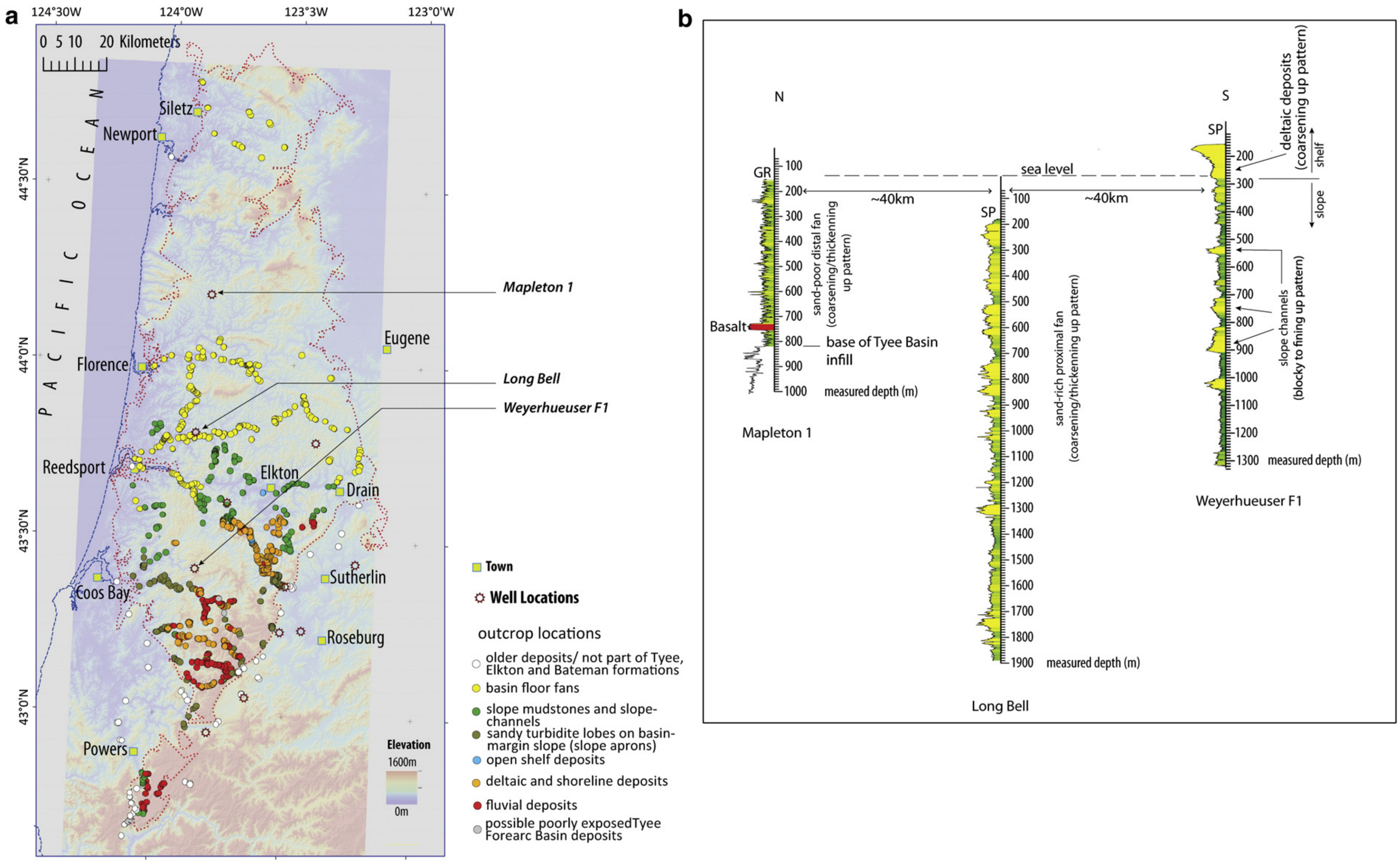


Fig. 5. Outcrop and subsurface data from Tyee Forearc Basin. a. Elevation map of study area showing color-coded outcrop locations and well locations, approximate boundary of Tyee Forearc Basin outcrop area also shown; locations of the three wells shown in panel b are highlighted. b. Interpreted well logs in three wells from southern, central, and northern Tyee Basin, well locations shown in panel a.

Table 2
Summary of lithofacies types identified within the Tyee Basin.

No.	Lithofacies name	Grain size	Bedding/set thickness	Sedimentary structure	Biogenic structures/fossil	Interpretation
L1	Thin-bedded fine-grained sandstone with/without grading	Very-fine to fine sand	Sharp-based thinly bedded (2–10 cm); upper boundary gradual	Ripple lamination, plane-parallel lamination, normal grading — sand beds fine upward into siltstone–mudstone layers	Absent	Low concentration sand-poor turbidity current deposit
L2	Medium-bedded structureless sandstones	Lower to upper medium-grained sand	Sharp-based, bed thickness — 20 cm to 1 m, sand amalgamation rare	Massive, to weakly normal graded, loading common at the base	Rare, locally abundant mud-lined vertical burrows (*Ophiomorpha*?)	High concentration sandy turbidity current deposit
L3a	Thick-bedded structureless sandstone with/without mud clasts	Lower to upper medium-grained sand, mud clasts 5–10 cm	Sharp-based, bed thickness — 1 m to 5 m, amalgamation common	Structureless, loading at the base rare, mud clasts present in certain locations, weak grading at the top of beds (top 2 cm)	Rare but locally abundant vertical burrows (*Ophiomorpha*?)	High concentration sandy turbidity current deposit
L3b	Thick-bedded structureless sandstone with very large mudstone clast	Lower to upper medium-grained sand, mudstone clasts up to 5 m in diameter	Sharp-based, amalgamated, very thick-bedded, bed thickness 1 m–5 m, bedding often disrupted by the large mud clasts	Structureless, clasts are composed of laminated mudstone	Absent	High concentration sandy turbidity current deposit with possible canyon wall-collapse deposits
L4	Pebbly sandstone	Medium-grained sand, pebble size up to 5 cm	Boundary gradational with L3	Indistinct imbrications, large-scale inclined surfaces (?)	Absent	Traction deposit (?) from high concentration turbidity current
L5	Sandstone and mudstone clast conglomerate	Variable matrix-mud to sand, clast-size variable (up to 20 cm)	Irregular top, base and lateral boundaries	Structureless, no bedding preserved, clasts show internal bedding	Absent	Slump/mass transport deposits
L6	Deformed sandstones with thin discontinuous mudstones with/without pebbles	Predominantly upper fine- to medium grained sand, mud, pebbles (when present) 2–5 cm	Irregular poorly defined upper and lower boundary, bedding poorly preserved, locally appears thin-bedded	Deformed, contorted indistinct bedding	Absent	Slump deposits
L7	Structureless sandy mudstones with clasts and plant debris	Mud and very fine sand with mudstone clasts, clast size variable (1–10 cm)	Thick-bedded (>1 m), sharp-based	Mudstone clasts, plant fragments relatively uncommon	Absent	Debris flow deposit
L8	Laminated mudstone	Silt and clay	Thickness 2–5 cm	Planar lamination, asymmetric ripple	Extremely rare, locally contains vertical sand-filled burrows	Fine-grained turbidites and hemipelagic deposits
L9	Laminated siltstone-mudstone and very fine sand with marine trace	Very fine-grained sand to mud	Bed thickness 2–10 cm	Planar lamination, asymmetric ripple, wave ripple	Rare *Asterosoma*	Deposition dominated by suspended fines, reworked by unidirectional currents and wave
L10	Hummocky cross-stratified sandstone	Very fine-grained sand	Thickness 50 cm to 1 m	Hummocky cross stratification, wave ripple	Rare oyster, *Ophiomorpha*	Storm wave generated deposit
L11	Thick sandstone units with planar bedding/low angle inclined bedding	Fine to lower medium-grained sand	Very thick units, >1 m	Parallel lamination to gently inclined bedding, indistinct planar & trough cross-beds	Oyster, rare *Ophiomorpha*	Possible wave re-worked sediment
L12	Small-scale cross-stratified sand stones with/without prominent mud-drapes	Fine to lower medium-grained sand and mud in thin layers	Set thickness 10cm–50 cm	Cross stratification with thin mud and mica-rich drapes, often bi-directional	Abundant marine trace fossils, common Teredolites at the base, Ophiomorpha	Bi-directional current, marine influence
L13	Large scale cross-stratified sandstone with marine traces	Medium-grained sandstone	Set thickness >1 m	Large scale planar to trough cross-stratification with mud-layers on cross-strata	Abundant marine trace fossils, common Teredolites, rare Ophiomorpha, oysters	Strong unidirectional current and slack periods, marine influence
L14	Ripple laminated fine sandstones with marine traces	Very fine- to fine-grained sand	Unit thickness variable, up to 1 m	Current ripples, often bidirectional, ripples have thin organic-matter rich drape	Common Ophiomorpha	Bi-directional currents, marine influence
L15	Heterolithic units with planar- to ripple-laminated sandstones and organic rich mud layers	Fine sandstones and organic rich mudstones	Bed thickness 1–2 cm	Planar lamination, current ripples, lenticular bedding and flaser bedding	Plant fragments common, marine trace fossil Teredolites	Influenced by unidirectional current and slack periods, marine influence
L16	Mudstone with/without thin coal beds with burrows	Mud	Lamination 2–5 cm, coal beds 2–10 cm	Planar lamination ripple lamination	Plant fragments common, Teredolites common	Suspension dominated deposit with marine influence
L17	Finely laminated organic-rich mudstone with thin coal beds	Mud to silt	Very finely laminated, <1 cm	Planar lamination	Coalified plant fragments	Suspension dominated deposit, non-marine
L18	Planar-stratified and ripple-laminated fine-grained sandstone and siltstone	Fine-grained sand to silt	Bed thickness 2–10 cm	Planar lamination/bedding, asymmetric ripple	Plant fragments	Suspension dominated deposits, non-marine
L19	Trough cross-stratified sandstones	Medium- to coarse-grained sand stone, rare granules, pebbles	Set thickness 50 cm to 2 m	Cross-stratified with foreset height 50 cm–2 m	Plant fragments	Strong unidirectional current, bedload dominated, non-marine
L20	Trough cross-stratified pebbly sandstone	Coarse-grained sand, pebble (long dimension up to 10 cm)	Foreset height 50 cm–2 m. foresets tabular to lensoid	Trough cross stratification	Coalified plant fragments very common	Strong unidirectional current, bedload dominated, non-marine

outcrop data. All outcrop information and the well-data were placed in a three-dimensional framework using standard 3D seismic interpretation software that allowed reconstruction of vertical profiles in arbitrary directions. The measured stratigraphic sections at the outcrop locations were treated as well data and were correlated across the basin. For each profile, a large number (100–300) of relatively

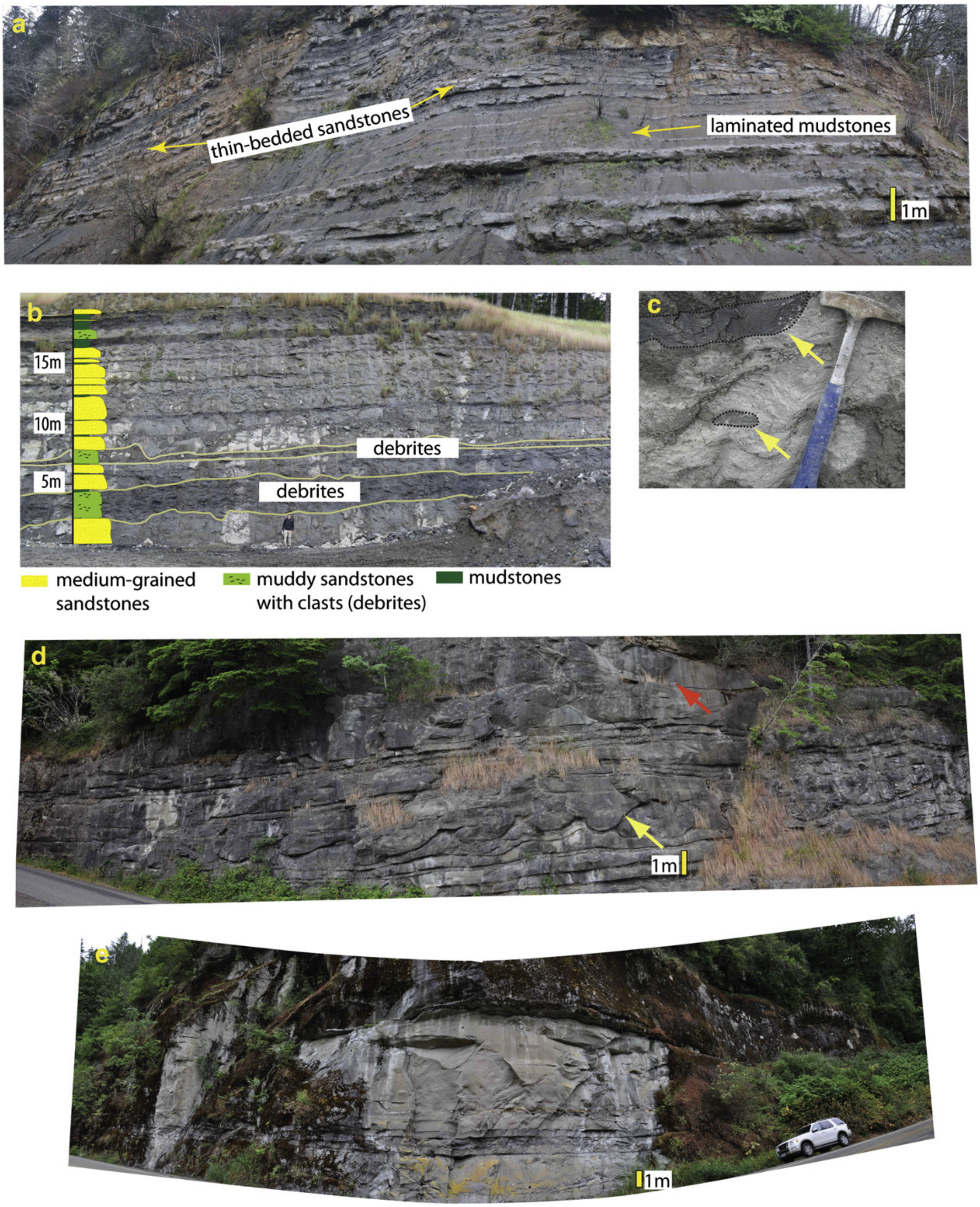


Fig. 6. Unconfined turbidite deposits of central and northern Tyee Forearc Basin — proximal and distal deepwater fan deposits; for lithofacies types (L) and lithofacies associations (FA) shown in the figure, see Tables 1 and 2; locations of the outcrops are shown in Fig. 10. a. Most distal sandy deepwater fan outcrop — laterally continuous thin-bedded sandstones (L1) and thick, laterally continuous layers of laminated mudstones (L8). b. Distal fan (FA 2) exposed in northern Tyee Forearc Basin — outcrop shows thin- and medium-bedded sandstones (L1, L2), thin laterally continuous mudstones (L8) and debris flow deposits (L7). c. Rip-up clasts within the debris flow deposits — distal fan outcrop, northern Tyee Forearc Basin. d. Proximal fan outcrop from central Tyee Forearc Basin (FA 2) — thick-bedded and medium-bedded laterally continuous sandstones (L2, L3a) and thin layers of laminated mudstones (L8), sandstone amalgamation (indicated by red arrow) is rare, pronounced loading at the base of sandstone layers (indicated by yellow arrow). e. Thick-bedded laterally continuous amalgamated sandstones (L3a) — proximal fan, exposed in central Tyee Forearc Basin.

short measured sections studied along multiple transects were combined to reconstruct the stratigraphy of the Tyee Forearc Succession at various scales. The correlations between outcrop locations are interpretive, as the outcrops are not very continuous in most areas of the basin, but the interpretations are consistent with topographic data and structural data at all locations.

Correlation of measured outcrops and well data across the basin resulted in several basin-wide cross sections that demonstrate the stacking pattern of non-marine, shelf, deepwater slope, and basin floor deposits. These basin-wide cross sections and the lithofacies map together provided good control on the three dimensional geometry of the basin-fill and allowed the stratigraphic reconstruction of shelf-margin clinothems, each of which includes topsets of fluvial to shoreline and shelf deposits, a muddy to sandy deepwater slope (foreset), and a sandy basin-floor fan component (bottomset). An important tool for reconstruction of the clinothems within the Tyee Forearc Succession has been the identification of a number of repetitive coarsening upward successions or parasequences within the fluvial/shallow-marine deposits of the southern Tyee Forearc Basin. These repetitive successions were recognized by their generally coarsening/thickening upward character, with a prominent and widespread fine-grained horizon at their bases in most cases. These successions have been correlated across the continental/shallow-marine succession of southern Tyee Forearc Basin and into the Tyee deepwater slope and basinal part of Tyee forearc succession. From this complex correlation exercise a first attempt at adding chronostratigraphic surfaces/trends to the Tyee Forearc Basin lithostratigraphy has been achieved, not simply conceptually but with ground-based information. This, in turn proved to be critical for several advances in our understanding of the basin-fill geometry. Clinoform reconstruction demonstrates that topset and slope strata in the basin fill accreted mainly in a transverse manner, whereas the and basin-floor turbidites swung longitudinally, sub-parallel with the tectonic grain along an older subduction trench.

4. Results

4.1. Lithofacies types and lithofacies associations

The clastic deposits of the Tyee Forearc Basin were subdivided into 21 lithofacies types on the basis of grain-size, sedimentary structures, bed thickness and biogenic traces (Table 2). The 21 litofacies types have been grouped into facies associations that are representative of various non-marine to deepwater depositional environments (Figs. 6–9). The locations of these outcrop photographs have been shown in Fig. 10.

Seven facies associations were identified across Tyee Forearc Basin that are dominated by turbidite deposits (Table 3), including FA 1 (fine-grained turbidite and hemipelagic suspension deposits), FA 2 (unconfined mud-rich sandy turbidite deposits), FA-3 (unconfined sandy turbidite deposits), FA 4 (unconfined/semiconfined turbidite deposits with evidence of instability), FA 5-1 (sandy turbidite channel-fills and overbank), FA 5-2 (sandy slope canyon-fill) and FA 6 (sandy/muddy small channel/gully fill). FA 5-2 is very restricted in its occurrence, being limited to a series of outcrops in southern-most outcrop areas of the Tyee Forearc Succession. Eight facies associations represent shallow-marine and non-marine deposits (Table 3): FA 7 (open marine mudstone), FA 8 (storm-dominated shelf deposits), FA 9 (wave dominated shoreface deposits), FA 10 (tide-dominated paralic deposits), FA 11 (tidal channel deposits), FA 12 (incised valley-fill — fluvial), FA 13 (point bar and flood plain deposits) and FA 14 (braided river deposits).

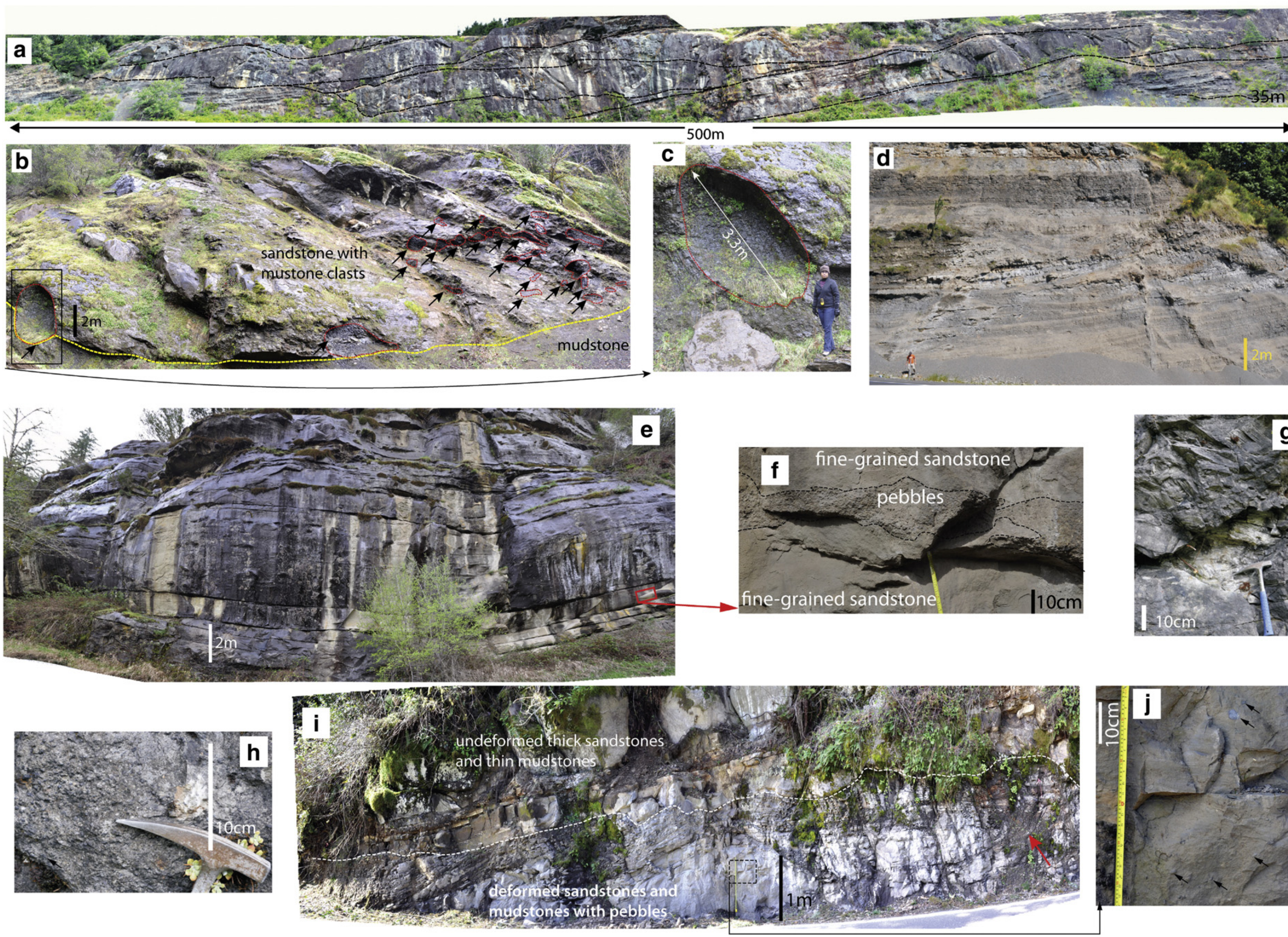
4.2. Facies distribution

The areal distribution of the facies associations shows that the fluvial to shallow-marine deposits, slope deposits, and basin-floor deposits of Tyee Forearc Basin (Fig. 11a,b) are not distributed in simple outcrop belts that show a deepening trend towards north as suggested in some previous publications (Lovell, 1969; Chan and Dott, 1983; Heller and Dickinson, 1985). The distribution pattern of non-marine, shallow marine and deepwater outcrops in the Tyee Forearc Basin is more complex; the result of the lithofacies stacking patterns generated by prograding/agrading basin fill, the effect of later structural deformation, and the present day topography of the Coast Range. For convenience of description, Tyee Forearc Succession outcrop area has been subdivided into (1) Southern Outcrop Area, (2) Central Outcrop Area and (3) Northern Outcrop Area, without assuming any stratigraphic or tectonic connotation for these subdivisions (Fig. 11a) except that the southern outcrop area is limited mostly to the south of the basement high known as the Umpqua Arch mentioned earlier in the article. It is important to note that the facies distribution described here is limited to the micaceous sandstones and fine-grained clastic deposits (siltstones and minor mudstones) of the stratigraphic units known as the Tyee Formation, Elkton Formation and the Bateman Formation, and does not include the older, and more deformed sediments of the Umpqua Group. The deposits of the Tyee Formation are usually easily distinguishable from older Umpqua Group by their gently deformed/undeformed character as well as by the abundance of mica in the sandstones.

4.2.1. Southern outcrop area

An elevation map of the southern Coast Range of Oregon (Fig. 11b) shows a prominent NNE–SSW-oriented topographic break that defines the south-east boundary of the Tyee Forearc Succession outcrop area. East of this topographic break muddy turbidites and shallow marine sandstones of underlying Umpqua Group are exposed (Fig. 11b). A narrow belt of turbidites and mass transport deposits of the Tyee Formation including small scale sandy to muddy channels (FA 4B) and sandy slope aprons (FA 3) are exposed along the topographic break and immediately west of it. These turbidites directly overlie the older, more deformed siltstones of Umpqua Group. Non-marine and shallow marine deposits of Tyee Forearc Succession including fluvial deposits (FA-13), tidal channel sandstones (FA 11), tide-dominated paralic deposits (FA 10) and shoreface deposits (FA 9) are extensively exposed in the topographically high areas west of this topographic break. The lower part of this fluvio-deltaic succession is dominated by stacked fluvial sandstones (FA 13) that are exposed near the eastern and western flanks of the topographic high. Turbidite deposits (sandy slope-aprons and fine-grained slope deposits) that underlie this predominantly fluvial succession are locally exposed along deeply entrenched river valleys that transect this highland. Similar turbidite deposits are exposed along

Fig. 7. Outcrop examples of channelized turbidite deposits (panels a–c), laterally extensive fine-grained slope turbidites of central Tyee Forearc Basin (panel d), and unconfined sandy turbidite deposits of southern Tyee Forearc Basin with associated deformed sediments; for lithofacies types (L) and lithofacies associations (FA) shown in the figure, see Tables 1 and 2; locations of the outcrops are shown in Fig. 10. a. Partly exposed turbidite channel complex (FA 5-1) in central Tyee Forearc Basin, showing at least five channel elements (separated by black broken lines in the figure), composed of thick-bedded amalgamated sandstones (L3a). b. Partly exposed canyon-fill (FA 5-2) in southern-most Tyee outcrop area showing very large mudstone blocks, outlined and marked by black arrows in the figure, within very thick-bedded amalgamated sandstone (L3b), yellow broken line indicates the incisional contact between sandy canyon-fill and underlying laminated mudstone. c. Large mudstone block (diameter > 3 m) in canyon-fill. d. Laterally continuous laminated siltstone and mudstone in central Tyee Forearc Basin. e. Outcrop example of thick-bedded, tabular, locally pebbly, sandstones (L4) with variable degree of amalgamation and associated deformed layers — from southern Tyee Forearc Basin. f. Deformed gravel-rich zones within the thick-bedded sandstone in panel e. g. Rip-up clast-rich zone within thick-bedded sandstone. h. Extra-basinal clast (pebbles)-rich zone in thick-bedded sandstone (L4). i. Extensively deformed zone (L6) associated with thick turbidite sandstones (L4), sandstone and mudstone layers are folded within the deformed zone, red arrow pointing at the hinge of a recumbent fold. j. distributed extra-basinal clasts (pebbles) within the deformed zone shown in panel i.


a
35m
500m
b
sandstone with
mustone clasts
2m
mudstone
c
3.3m
d
2m
e
2m
f
fine-grained sandstone
pebbles
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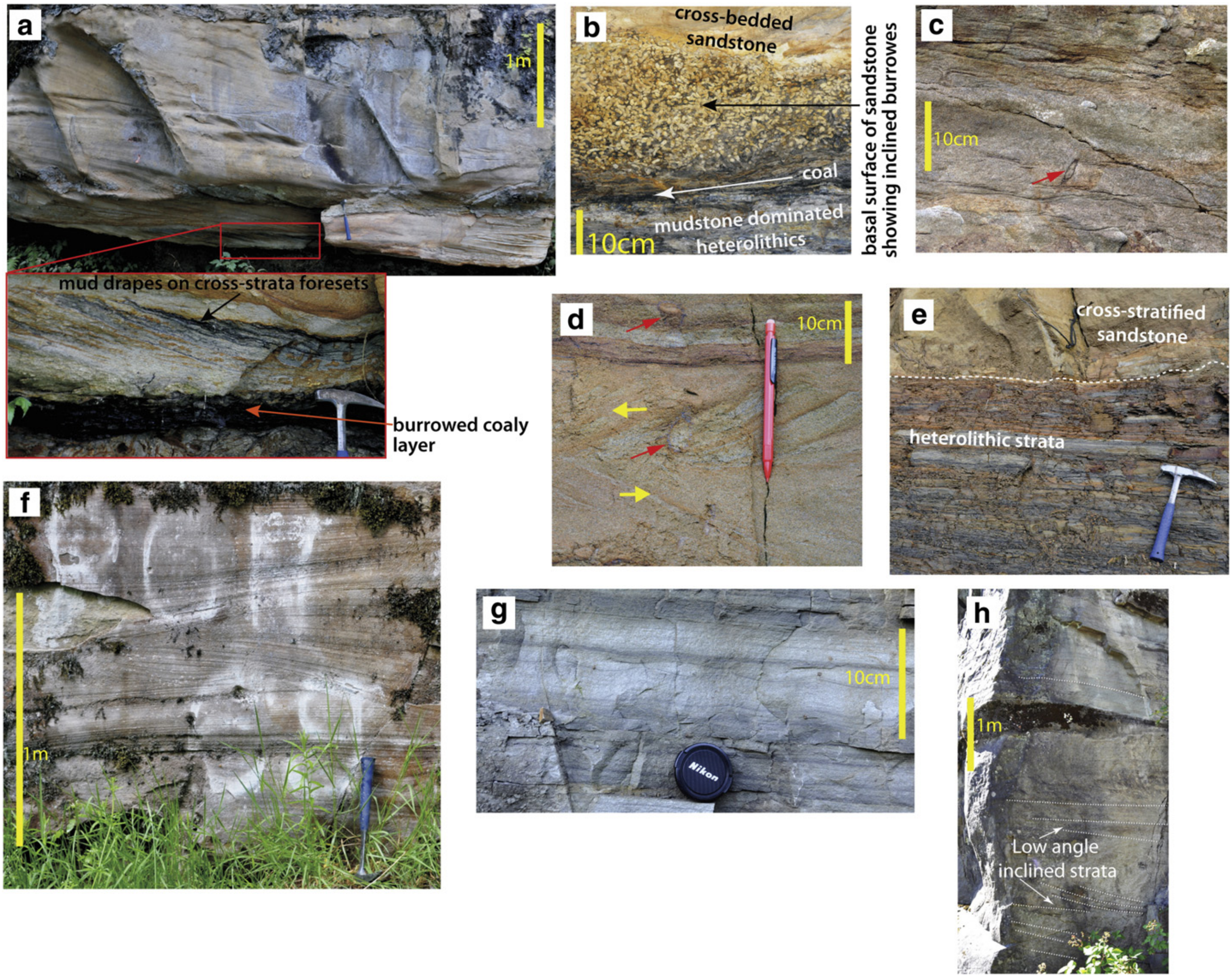

Fig. 8. Shallow marine deposits with strong tidal influence (a–e) and wave influence (f–h); for lithofacies types (L) and lithofacies associations (FA) shown in the figure, see Tables 1 and 2; locations of the outcrops are shown in Fig. 10. a. Cross-stratified thick sandstone (L13) with burrowed organic-rich layer below, distinct organic material-rich mud drapes on cross-strata foresets. b. Sand-filled burrows exposed on basal surface of sandstone (L13), organic-rich mudstone layer bellow the sandstone was extensively burrowed, possible *Teredolites*. c. Ripple laminated fine-grained sandstone (L14) with *Ophiomorpha* (indicated by red arrow). d. Cross stratified sandstone (L12) showing opposing cross-strata foreset dips (indicated by yellow arrows); *Ophiomorpha* burrows common (indicated by red arrow). e. Ripple laminated/plane laminated heterolithic strata and overlying cross-stratified sandstone (L12) with sharp basal contact. f. Hummocky cross-stratified fine-grained sandstone (L10, FA 9) — lower shoreface deposits from southern Tyee Forearc Basin. g. Wave ripples in fine-grained sandstone — southern Tyee Forearc Basin. h. Part of thick (>15 m) medium-grained sandstone body with low angle inclined stratification — upper shoreface deposit from central Tyee Forearc Basin.

the base of the gently sloping western flank of this topographic high. Older (Umpqua group) fine-grained deepwater deposits and underlying basaltic basement rocks are exposed farther to the south-west beyond the Tyee outcrop area. Younger (Late Eocene) deposits of Coos bay Basin are exposed farther south-west towards the Coast. The above-mentioned outcrop distribution pattern shows that the Tyee Forearc Succession in the southern outcrop area includes thick turbidite deposits at the base overlain by predominantly fluvial sandstones which in turn are overlain by a thick succession of fluvial and shallow marine sandstones (Fig. 12a).

The southernmost Tyee outcrops are restricted to a small topographic high south and east of the town of Powers (Fig. 11a,b) where a belt of slope mudstones and slope canyon sandstones (FA 5-2) appear to be directly overlain by a set of fluvial sandstones and conglomerates. The Eastern boundary of this outcrop area is controlled by a north-westerly dipping fault zone and in this area fluvial deposits of Tyee Forearc Basin succession are directly in contact with siltstones of older Umpqua Group.

4.2.2. Central outcrop area

The Central outcrop area is bounded to the east by the northward extension of the topographic break mentioned in the previous section. To the west Tyee outcrops extend to the modern dune fields near the Pacific Coast. Sandy basin-floor fans (FA 2), slope channel sandstones (FA 5-1) and fine-grained turbidite deposits are exposed over the major part of the Central Outcrop Area (Fig. 11b). Outcrops of non-marine and shallow marine deposits are restricted to the southern part of this area (Fig. 11a). Sandy slope channel fills (FA 5-1) and muddy slope deposits (FA 1) are exposed along the south-eastern margin of the Central Outcrop Area that had been previously identified as a part of the Hubbard Creek member of the Tyee Formation. The slope deposits are overlain by non-marine and shallow-marine deposits (with possible interfingering) that are exposed in a broad central area roughly bounded to the north and to the east by Umpqua River Valley. These thick fluvial sandstones (FA-14), tidal channel sandstones (FA-11), shoreface sandstones (FA-10) and fine-grained storm-dominated shelf sandstones (FA-9) have been identified as the Baughman member of

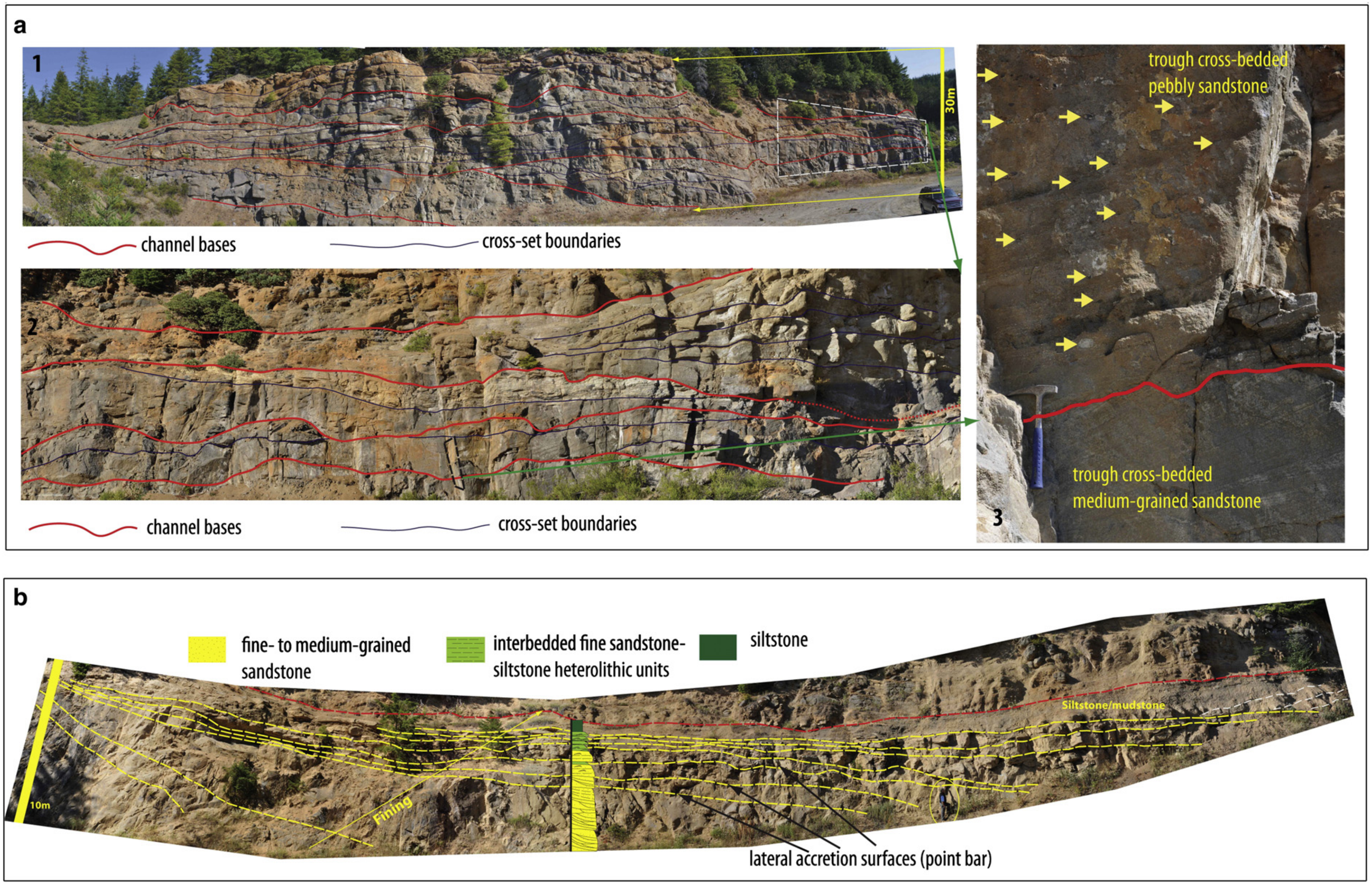

Fig. 9. Outcrop examples of fluvial deposits — southern Tyee Forearc Basin; coarse-grained braided river deposit with pebbles (Fig. a-1, 2, 3), and fining upward pointbar deposits with associated muddy flood-plain deposits (panel b); locations of the outcrops are shown in Fig. 10. a. ~30 m high outcrop (panel a-1) in southern Tyee Forearc Basin showing stacked multiple channel fills (FA 14) composed of pebbly coarse-grained trough cross-stratified sandstone (L20) and medium-grained trough cross-stratified sandstone (L19) — red lines mark channel-bases, thin blue lines separate cross-strata sets; inset (panel a-2) shows close-up of four stacked channels with coarse-grained cross-stratified channel-fills; farther inset (panel a-3) shows a channel base marked by facies change from underlying medium-grained cross-stratified sandstone and overlying pebbly coarse trough cross-stratified sandstone — black arrows point to disseminated pebbles within cross-set. b. Fining upward fluvial deposits (FA 13), composed predominantly of medium-grained sandstone (L19) at the base fining upward into fine-grained sandstones (L18) and mudstones (L17); yellow broken lines represent the lateral accretion surfaces, red line represents base of overlying sandy unit.

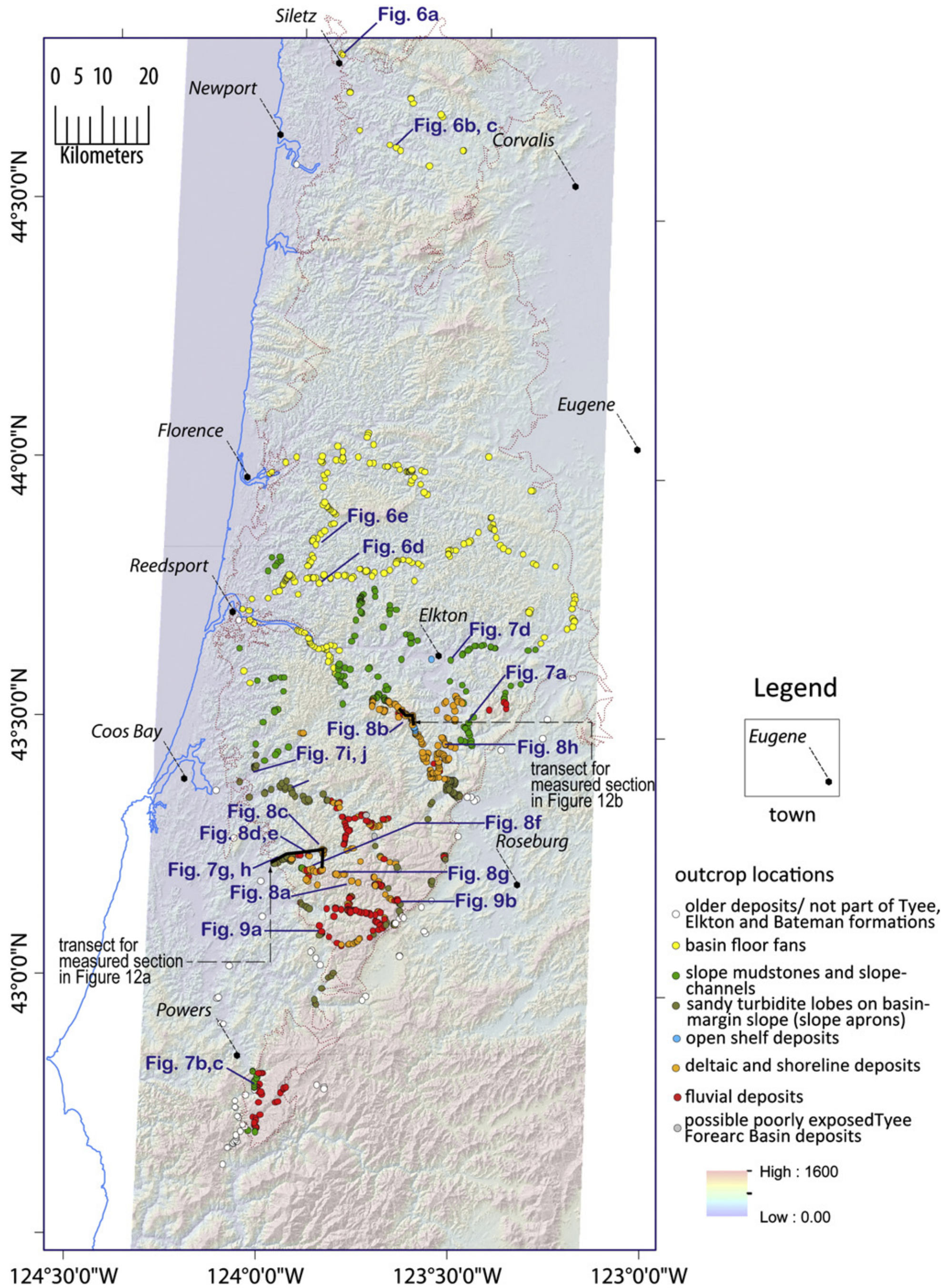

Fig. 10. Location map for the outcrop photographs shown in Figs. 6–9; map also shows the position of the transects represented by the stratigraphic sections in Fig. 11.

Tyee Formation. Younger slope deposits (FA 5-1: channel fills, FA-1: slope mudstones), previously interpreted as part of the Elkton Formation are exposed farther to the north, west and south-west of the town of Elkton. The youngest non-marine and shallow marine deposits of the Tyee Forearc Succession (previously identified as the Bateman Formation) that include tidal channel sandstones (FA-11), other tide-dominated paralic deposits (FA-10) and thick sandy incised-valley fills (FA-12), are exposed in a topographic high (Figs. 11a,b and 12b) south of the Umpqua River valley. This predominantly sandy succession is underlain by a thick open-marine mudstone (FA-8) that outcrops along the southern flank of this topographic high (Fig. 11a). This fine-grained unit appears to pinch out to the south and thickens to the north ultimately merging with the slope mudstones of the Elkton Formation. In the southern part of Central Outcrop Area this mudstone unit separates the two predominantly sandy units — the underlying Baughman member of Tyee Formation and the overlying Bateman Formation.

Sandy proximal basin-floor fan deposits (FA-3) are exposed in the northern half of the Central outcrop Area north of the Umpqua River Valley. In the northern half of Central Outcrop Area the Smith River Valley represents an excellent outcrop transect for the these thick sandy basin-floor fans where estimated cumulative thickness of these stacked basin-floor fans appear to be nearly 2000 m (measured from outcrop and well data).

4.2.3. Northern outcrop area

Exclusively deepwater fan deposits are exposed in the Northern Outcrop Area. Thick, tabular, turbidite sandstones (FA-3) are exposed in southern part (Siuslaw River Valley). Relatively mud-rich distal fan deposits (FA-2) and extensive fine-grained turbidite deposits (FA-1)

Table 3
Summary of facies associations.

Facies associations	Constituent lithofacies	Description	Interpretation
FA 1	L8	Uniform laterally extensive finely laminated mudstone/siltstone (L8); rare scour and fill	*Fine-grained turbidites and hemipelagic deposits* on slope and basin-floor
FA 2	L1, L2, L7, L8	Individual 20–30 m thick units composed of thin-bedded to medium-bedded laterally extensive sandstone (L1, L2) units interbedded with thick (up to 2 m) finely laminated mudstones (L8) and sandy to muddy debris flow deposits (L7) (up to 3 m thick, with irregular top and base and high concentration of mud rip up clasts and plant fragments); thick finely laminated mudstone packages (>2 m) separate the 20–30 m thick units	*Unconfined mud-rich sandy turbidite deposits* — distal fan deposits
FA 3	Rare L1, abundant L2, L3, L8	Highly sand-rich, >35 m thick units composed of structureless thick- to medium-bedded laterally extensive sandstones (L2, L3) and thin (2–10 cm) usually laterally continuous mudstones (L8); thin-bedded graded sandstone beds (Facies A3) are relatively rare; sand bed amalgamation common, extensive loading at the base of thick-bedded sandstone; thick (1–2 m) laminated mudstone layers separate individual sand-rich units	*Unconfined/semi-confined sandy turbidite deposits* — proximal fan deposits
FA 4	L2, L3a, L4, L6, L8; rare L1	Tabular sand-rich units without clear vertical organization, composed of thick-bedded and medium-bedded structureless sandstones (L2, L3a), deformed (possibly slumped) sandstones with thin mudstone layers (L6) occasionally containing pebbles, rare thin-bedded mudstones (L8), and rare lenses of pebbly sandstone (L4) — no evidence of large-scale erosion at the bases of sandstone beds	*Unconfined/semi-confined sandy turbidite deposit with evidence of instability* — possible slope apron
FA 5-1	L3a, L2, rare L1 and L8	Individual sandy units encased within extensive mudstones, with marked erosion at the base, up to 25 m thick, lensoid in cross section, composed of thick amalgamated sandstones (bed thickness 1–5 m) (L3a) that tend to become thinner and less amalgamated laterally over 100 s of m, changing into medium- to thin-bedded sandstones (L2, L1) interbedded with very thin mudstone layers (L8); vertically and laterally stacked sandy units form large complexes with possibly up to 100 m thick, sandy fills; both sand to sand contacts and sand to mudstone contacts at the base of the units common, unit base marked by high concentration of mudstone rip-up clasts; no evidence clearly suggests that the individual sandy units in the complexes occupy a larger (>50 m deep) erosional feature	Laterally and vertically stacked *sandy turbidite channel-fills* forming large channel complexes
FA 5-2	L3a, L3b, rare L4	Extremely thick (>60 m) sandstone package with distinct erosive basal (and lateral) contact with underlying mudstone, composed of thick-bedded amalgamated sandstone beds without/with large mudstone clasts (L3a/L3b) and rare pebbly sandstones (L4) — abundant very large mudstone clasts (up to 5 m in diameter), often angular, near the observed lateral boundary of the sandstone package with underlying mudstones.	*Sandy slope canyon-fill* with possible canyon wall collapse deposits
FA 6	L8, L1 and rare L2	Small (10s of m wide, <10 m deep) erosion features within uniform fine-grained turbidite deposits (mudstones and rare thin-bedded sandstones) (L8, L1), filled with fine-grained turbidites or sandy turbidites (L1 and L8); soft-sediment deformation common — found in close spatial association with cross-bedded shallow-marine deposits in central and southern Tyee Basin	*Sandy/muddy small channel-/gully-fill* — at shelf edge or on upper-most slope
FA 7	L9	Thick units (5–10 m) of finely laminated mudstone-siltstone with minor thin-bedded sandstones — units show weak coarsening upward trend	*Shelf mudstone* deposited on drowned distal shelf
FA 8	L9, L10	Repeated 3–5 m thick units with planar laminated and ripple laminated (containing symmetric and asymmetric ripples) mudstones (L9) at the base, overlain by hummocky cross-stratified very fine-grained sandstones (L10)	*Storm dominated shelf deposits*
FA 9	L10, L11	Repeated 15–20 m thick sandy units with 2–3 m thick hummocky cross stratified sandstone (L10) at the base overlain by very thick (>10 m) low angle cross-stratified to planar stratified sandstone unit (L11)	*Wave dominated shoreface deposits*
FA 10	L12, L13, L14, L15, L16	Repeated ~20 m thick cycles consisting of very thick (>15 m) cross-stratified sandy unit with varying foreset height (L12, L13), overlain by ~1 m thick ripple laminated very fine sandstone unit (L14), overlain by 2 m thick unit with heterolithics (L15) and mudstone with thin coal layer (2–10 cm) on top; coal layer extensively burrowed (*Teredolites*) — burrows filled by sand from lowest unit of overlying cycle	*Tide dominated paralic deposits* with thick sandy subtidal unit, thin intertidal unit and muddy organic rich supratidal unit — transgressive?
FA11	L12, L15	Thick (up to 10 m) cross-stratified sandstone (L12) unit with erosive base overlying thick uniform heterolithic unit (L15) containing fine-grained sandstones and mudstones with mud-draped planar beds, mud-draped ripples, flaser and lenticular beds; cross-beds within the sandy unit often indicate bidirectional current; cross-bed foreset height varies (20 cm–1 m), marine traces common (*Ophiomorpha*, *Teredolites*)	*Tidal channel fill and tidal flat*
FA12	L18	Very thick sandy unit (>35 m) composed of stacked trough cross-stratified sandstones (L18) with indistinct fining upward trend, no marine traces, base of the unit distinctly erosional (10 s of m erosional relief) cutting down into underlying tidally influenced paralic deposits	*Non-marine incised valley fill* (fluvial)
FA13	L17, L18, L19	Up to 20 m thick fining upward predominantly sandy units with distinct erosion surface at the base and distinct low angle lateral accretion surfaces; from base to top units consist of trough cross-bedded thick sands with rare pebbles and granules at the base (L19), planar laminated and ripple laminated fine sandstones, heterolithic units with mud-draped ripple laminated and planar-laminated sandstones (L18), and mudstone (L17) with plant fragments; thin coal beds (up to 30 cm) are common below the erosive base of the fining upward sandy units	*Point bar and flood plain deposits*
FA14	L18, L19, L20	Stacked trough cross-bedded pebbly sandstone units with strongly erosive bases; individual units (4–10 m thick, 10s of m in lateral extent) appear to be slightly fining upward — from pebbly coarse sandstone(L20) with large trough cross-beds at the base, followed by trough cross-bedded coarse to medium-grained sandstones (L19) and thin (<1 m) planar-laminated and ripple laminated heterolithic units (L18) at the top	*Braided channel deposits* — fluvial

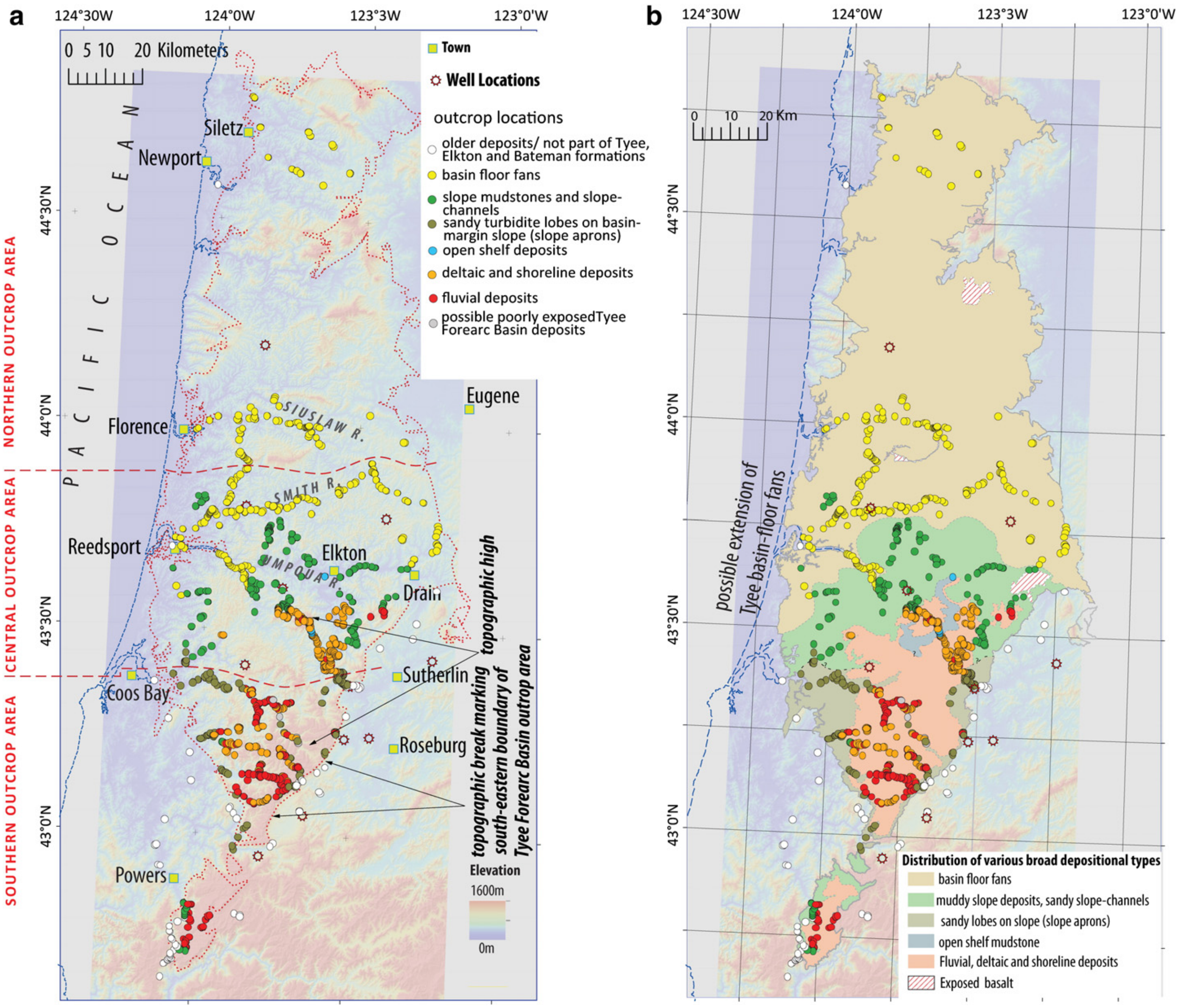

Fig. 11. Distribution of various broad facies groups in the Tyee Forearc Basin (panel b) and elevation map of the study area showing major topographic features in the study area (panel a). a. Elevation map of the study area showing major topographic features and the three-part subdivision of the Tyee Forearc Basin outcrop area used for explanation of the distribution of various facies groups in the text. b. Map showing distribution of five broad facies groups and inferred facies boundaries in Tyee outcrop area.

are exposed in the northern part (Alsea River Valley and Siletz River Valley; Fig. 11a,b). In the western flank of the Northern Outcrop Area, younger basaltic volcanic rocks (Yachat Basalt) are exposed near the Pacific Coast. North of the northern-most Tyee outcrops the basaltic basement (Siletz River Volcanics) is exposed. The exposed basement has been interpreted as part of a basement high that extends farther south, below the Tyee deepwater deposits (Snavely and Wagner, 1963). It has been reported that early to Middle Eocene basaltic sandstones and siltstones (probably equivalent in age with deepwater sandstones of Tyee Mountain member of Tyee Formation but genetically unrelated) are present on the western flank of this basement feature (Bukry and Snavely, 1988). The presence of these basaltic sands indicates that the abovementioned basement high is a pre-existing structure that restricted the westward extent of the Tyee deep water fans to its eastern flank. The basin axis to the east of this basement high, that accumulated thick fan succession, appears to be parallel to the suture zone along which Siletz River Volcanic Terrane was accreted, and may represent an inherited topography from the inactive Early Eocene trench.

4.3. Paleo-transport & Paleogeography

Paleo-current data from parts of the Tyee Forearc Basin have been discussed by a number of workers in the past (Snavely et al., 1964; Lovell, 1969; Chan and Dott, 1983). It is important to note that the observed paleo-current indicators have been affected by post-Early Eocene clock-wise rotation (>65°) of the Tyee Forearc Basin and all the paleo-current data discussed in this article are relative to the present day orientation. An average northward paleo-current direction has been identified by Snavely et al. (1964) from Tyee turbidite deposits (Fig. 13a). Chan and Dott (1983) presented paleo-current information from both shallow and deepwater deposits of so-called 'Fluornoy-Tyee' (Fig. 13b), which also show average northward paleo-transport. Heller et al. (1984) concluded from their petrographic study that the Tyee sediments were derived from a granitic source to the east, as opposed to the southern (Klamath Mountains-derived) source for the pre-Tyee sediments, though they did not show any westerly paleo-transport data.

Paleo-current data (n = 307) from the present study, acquired from non-marine, shallow marine and deepwater deposits of Tyee Forearc

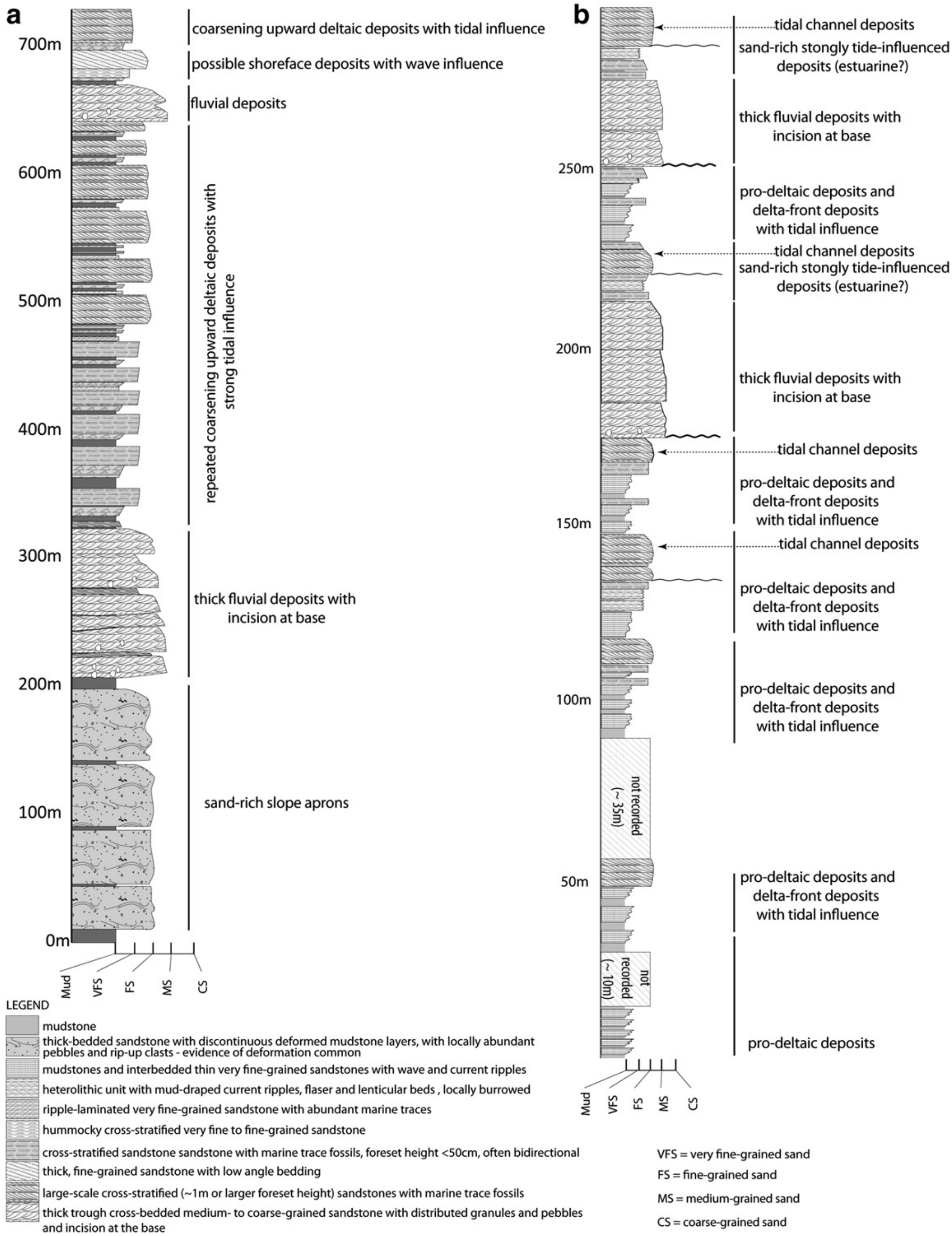

Fig. 12. Simplified partial stratigraphic sections from southern and central Tyee Basin; sections are results of combination of a large number of relatively short measured sections studied along a number of transects — locations of transects has been shown in Fig. 10. a. A combined section from south-western part of the Tyee Forearc Basin outcrop area shows the sandy slope-aprons at its base, overlain by thick fluvial deposits and an overlying fluvial-shallow-marine succession. The deltaic/shallow-marine deposits record strong tidal influence. Evidence of wave influence is present only at the topmost part of the section. b. A combined section from central part of the Tyee Forearc Basin outcrop area showing a number of coarsening/shallowing upward sediment packages of varying thicknesses; the section represents relatively younger part of the fluvial to shallow marine deposits of the Tyee Forearc Basin (Bateman Formation in the stratigraphic column shown in Table 1).

Basin, show significant variability in paleoflow directions and a complex sediment transport pattern (Fig. 13c). Paleo-current indicators (cross-stratification and ripples) from fluvial and shallow marine deposits in southern and central areas strongly suggest that the basin was fed by multiple fluvial supply systems from the east (transverse to the basin-axis — *transverse* input) across a relatively wide area. This is consistent with the provenance of the Tyee sandstones as identified by Heller et al. (1984) and effective line-source like behavior described by Chan and Dott (1983). The average transport direction recorded from fluvial and shallow marine deposits of Tyee Forearc Basin is towards north-west. The paleo-current data recorded from the slope deposits (slope-channels) in central Tyee Forearc Basin indicate north-westward

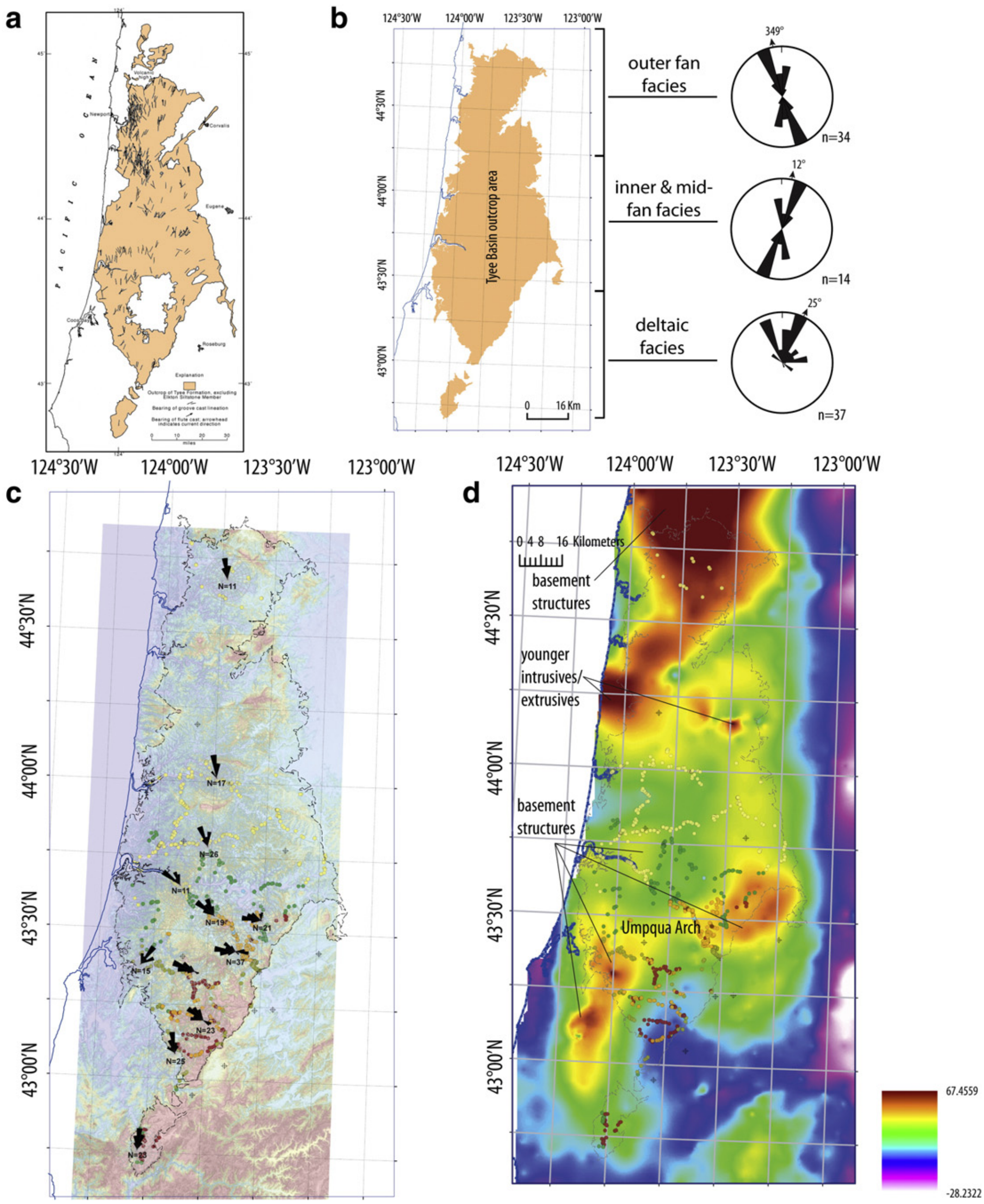

Fig. 13. Paleo-current distribution and basement structures in the Tyee Forearc Basin. a. Published paleo-current data from Snavely et al. (1964), based on observation from turbidite deposits. b. Paleo-current data from 'deltaic facies', 'inner and mid-fan facies', and 'outer fan facies' of Tyee Basin, redrawn after Chan and Dott (1983). c. Paleo-current data recorded in present study from non-marine, shallow marine, and deepwater deposits of Tyee Forearc Basin, data include cross-strata dip-direction and flute cast orientation. d. Isostatic gravity anomaly map of study area (data from Roberts et al., 2008) showing areas of strong positive gravity anomaly (in warm colors) that indicate basement structures or younger igneous rocks near surface.

sediment transport in the early stage that changed to average northward transport in a later stage. The paleo-current data acquired from the basinal parts of the Tyee Forearc Succession show that the major pathways of sediment transport *within* the basin (the direction of progradation of the deepwater fans) were from south to north. A number of local variations in sediment transport directions were also observed, probably reflecting pre-existing basement topography (Fig. 13d) within the basin that locally deflected the turbidity currents. For example, anomalous east-north-eastward transport directions were recorded from sandy turbidite deposits near the south-western margin of Tyee outcrop area which is flanked by a possible basement structure to the west.

4.4. Paleotopography of Tyee Forearc Basin: influence of basement and other structure

The major elements that affected the paleogeography of the Tyee Forearc Basin include the position and orientation of the suture along which Siletz Terrane was accreted, the pre-existing basement structures on the accreted oceanic Siletz Terrane, and distribution of the pre-Tyee sediments that were significantly deformed before initiation of Tyee forearc sedimentation. The suture is thought to be located near the Wildlife Safari Fault, about 15 km east of the eastern boundary of the Tyee Forearc Basin outcrop area and has a roughly NNE–SSW orientation near the town of Roseburg (Fig. 14; Wells et al., 2000). Observations on the paleo-transport as discussed above indicate that the Tyee Forearc Basin received sediment across this suture zone, through multiple rivers that derived sediments from the continental interior further to the east.

Pre-Tyee clastics of Umpqua group are exposed west of the suture zone and east of the Tyee outcrop area (Fig. 14). These clastics include the pre- to syn-accretion and post accretion deposits accumulated before the initiation of forearc sedimentation within the Tyee Forearc Basin. The lower part of the Umpqua Group is highly deformed and represents part of the accretionary prism associated with the pre-Early Eocene subduction zone and deposits formed during the accretion of the Siletz River Volcanic Terrane. The younger part of the Umpqua Group, represented by the White Tail Ridge Formation (non-marine and shallow-marine) and Camas Valley Formation (open-marine and deepwater siltstones), are more gently deformed and were possibly deposited after the accretion of the Siletz Terrane, modifying the topography of this newly formed continental margin. The sediments of the Umpqua Group are thought to have been sourced from the south (Klamath Mountains). These sediments are very thick in the southern part of Coast Range and include both shallow marine/non-marine units and deepwater turbidite units. In the northern Coast Range, the Umpqua Group is much thinner and is represented by deepwater muddy turbidites. The thick pre-Tyee deposits in the southern Coast Range may have controlled the initial topography of the proximal parts of the Tyee Forearc Basin.

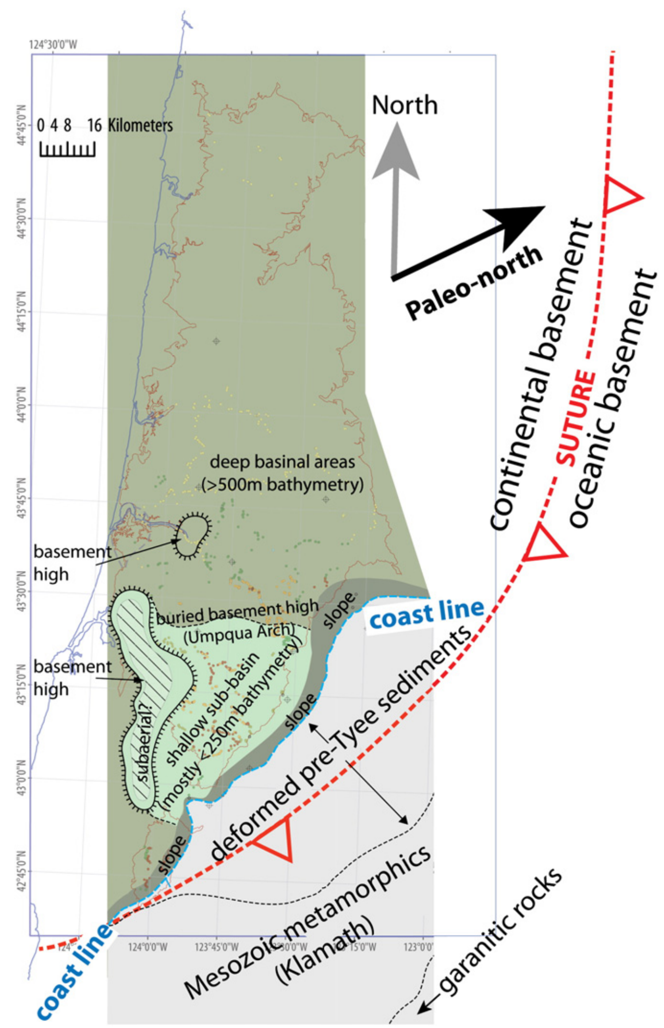

Fig. 14. Paleo-geography of Tyee margin at the initiation of forearc sedimentation showing shallow sub-basin south of Umpqua Arch; note, absence of any significant shelf at this stage and varying width of slope along strike. The location of the shelf break and the coast line is a result of extrapolation of the observations made from outcrop data. The stratigraphically lowest deposits of Tyee Forearc Basin along the south-eastern boundary of the Tyee Forearc Basin outcrop area are slope deposits, which are overlain by fluvial and shallow-marine deposits of slightly younger age, exposed further to the west. In view of the recorded average paleo-transport towards north-west, the fluvial and shallow marine deposits of the same age as the oldest slope deposits should lie beyond the south-eastern boundary of the present-day Tyee Forearc Basin outcrop area and assumed to be not preserved. As a result, the position of the coast line or the shelf break at the onset of the basin-filling process is not verifiable from direct outcrop observation. The coast line (and the shelf-edge) has been assumed to be located somewhat to the east of the south-eastern boundary of the Tyee Forearc Basin outcrop area and to be similar in orientation with the suture zone (roughly normal to the average sediment transport direction).

A gravity map of the southern Coast Range of Oregon (Roberts et al., 2008) shows a number of basement structures indicated by positive gravity anomalies (Fig. 11d). These basement features in the oceanic Siletz River Terrane are likely to have controlled the topography/bathymetry of the Tyee Forearc Basin and consequently the paleo-sediment transport of the non-marine as well as subaqueous (marine) deposits. A prominent ENE–WSW oriented linear basement feature known as the Umpqua Arch might have controlled the thickness and distribution of the pre-Tyee sediments of the Coast Range as indicated by significantly greater thickness of pre-Tyee sediments in the area south of Umpqua Arch as well as by the absence of any pre-Tyee shallow-marine/non-marine sediments north of this structure. This disparate distribution of late pre-Tyee sediments in turn controlled the initial configuration and topography/bathymetry of the Tyee Forearc Basin. We propose that at the initiation of forearc sedimentation a relatively shallow sub-basin existed in the southern part of the Tyee Forearc Basin south of the Umpqua Arch that was filled by sediments supplied from south-east (Fig. 14) as indicated by the paleocurrent data discussed above. Distribution of fluvial deposits in central Tyee Forearc Basin indicates that the deeper area of Tyee Forearc Basin north of Umpqua Arch also received direct sediment input as a result of the existence of multiple fluvial sources feeding the basin in a transverse direction. Nonetheless, a significant storage of sediment occurred in the relatively shallow southern sub-basin at the early stage of infilling of the Tyee Forearc Basin.

4.5. Clinoform enlargement at the basin margin through time

From detailed mapping and reconstruction of basin-wide cross sections in the southern and central Tyee Forearc Basin (Fig. 15a,b) two distinct stages of development of the basin-fill can be interpreted. These stages are distinct in terms of the height of the basin-margin clinoforms, progradation rate of the clinoforms and the distribution of lithology across the clinoforms. It is likely that these differences between the two stages hinged mainly on depositional water-depth (accommodation) change, from shallower to deeper stages, and that the early stage can be seen as an initial or embryonic phase of the basin-margin wedge development on this active margin (Fig. 16). At the initial stage of basin development, the clinoforms that formed and accreted across the southern, shallower part of the basin were of relatively small height (<250 m), which prograded rapidly and allowed only modest aggradation of their topsets. The preserved clinoform topset at this early stage is dominated by amalgamated fluvial deposits with evidence of only thin and discontinuous deposits with marine influence (Fig. 15a). The rarity of shallow marine deposits on the topsets of these early clinoforms is attributed partly to high fluvial sediment supply with repeated fluvial incision on the coastal prism, and partly to the relatively steep gradient of this initial, narrow topset segment that was to become the 'shelf'. Abundance of incisional features at the base of these early-stage clinoform topsets have been recognized by some earlier workers (e.g., Ryu et al., 1992) as an extensive basin-wide unconformity separating the fluvial-deltaic Baughman Member from underlying slope deposits of the Hubbard Creek Member. The incisional character is recognizable in

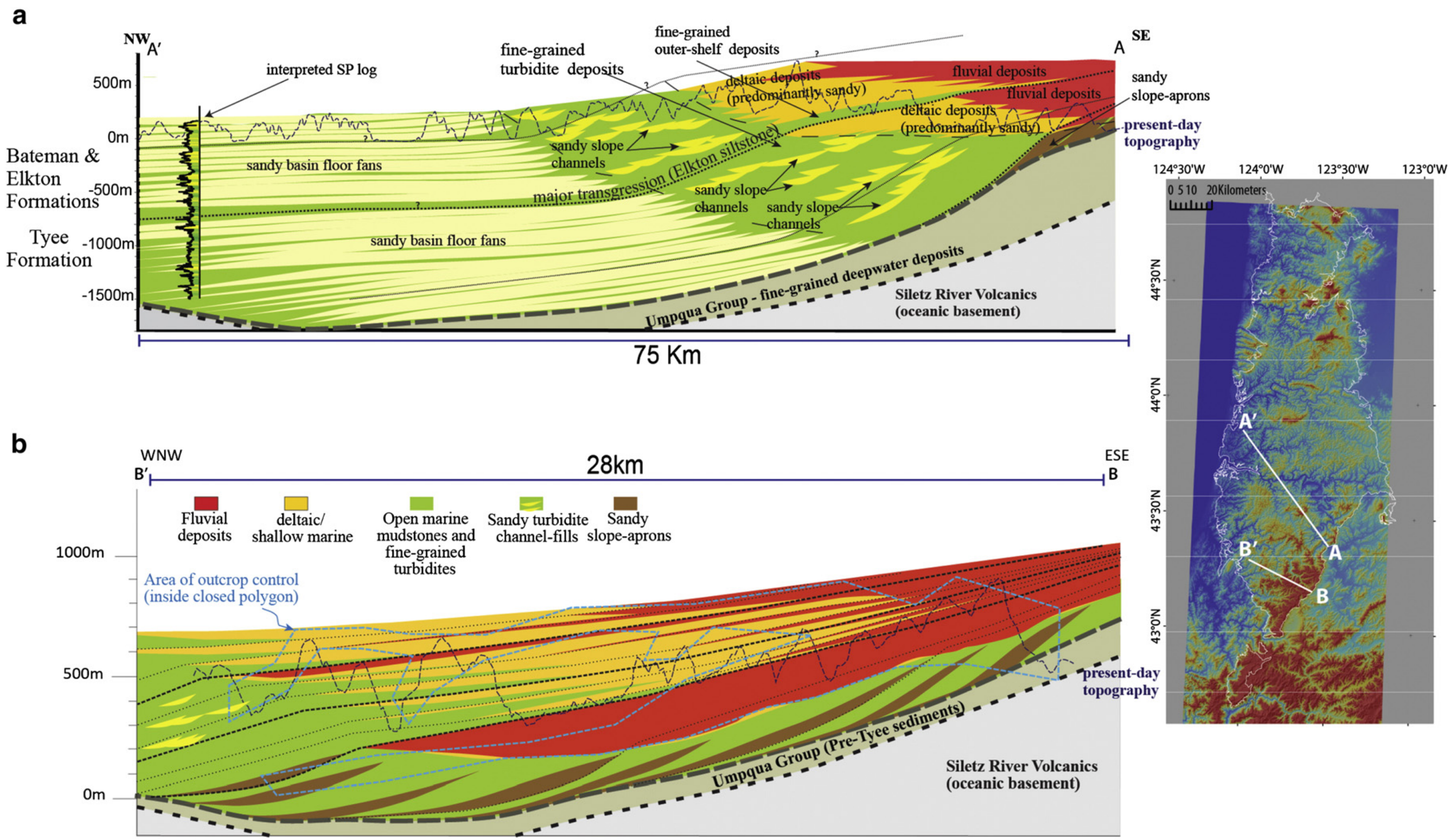

Fig. 15. Two regional cross sections showing clinoformal geometry of the Tyee Forearc Basin-fill. a. 75 km long cross section in central Tyee Forearc Basin (line A–A′ on the index map). b. 28 km long section in southern Tyee Forearc Basin (line B–B′ on the index map). Section AA′ is almost entirely north of Umpqua Arch and in this section the initial small clinoforms are not well-represented, while section BB′, which is in southern Tyee Forearc Basin (south of Umpqua Arch) demonstrates the two stage development of the basin-fill with initial highly progradational smaller clinoforms (topsets dominated by fluvial deposits, foresets dominated by sandy slope aprons), followed by larger, more aggradational clinoforms with well-developed fluvio-deltaic cycles on the topsets and well-organized turbidite channels on the foreset.

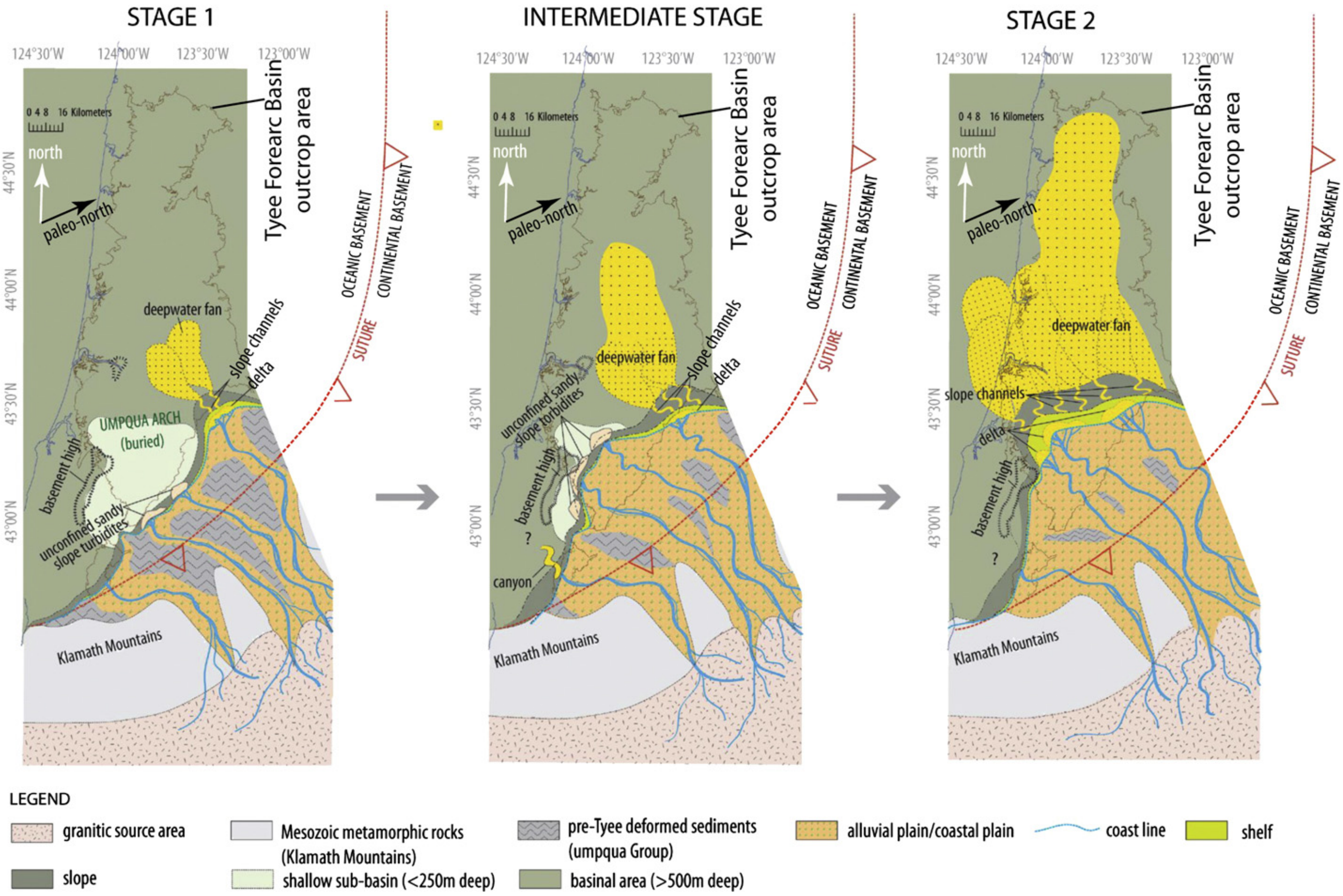

Fig. 16. Stages of development of the Tyee Forearc Basin-fill, showing the first stage (STAGE 1 and INTERMEDIATE STAGE) and second stage (STAGE 2) described in the text. First stage: STAGE 1 highlights the initiation of basin-filling by sediments supplied over a wide area by a number of rivers, presence of shallow sub-basin to the south, and variable basin-margin slope height and width; INTERMEDIATE STAGE highlights rapid progradation of the shelf edge across the shallow sub-basin and resultant change in orientation of the shelf-edge; note, sandy aprons develop on the basin-margin slope in southern Tyee Forearc Basin, while channels develop on the slope only near extreme northern end of the newly built margin. Second stage: STAGE 2 highlights the changed orientation of the shelf edge following progradation of shelf edge across the shallow sub-basin, existence of a relatively wide shelf, active turbidite channels on the basin-margin slope and extensive deepwater fan development.

southern part of Tyee Forearc Basin as well as in the central outcrop area near its eastern edge. In view of the new paleo-transport data (north-west direction of major paleo-transport in place of previously recognized northward paleo-transport), as well as from observation made on the extensive storm-dominated muddy/sandy shelf deposits seen in the Umpqua river valley ~12 km south of Elkton, we propose that the north–south extent of this time-transgressive, composite non-depositional/erosional surface is not indicative of its basinward extent, and that the incisional character is limited to the early stage of basin-filling when the clinoforms were strongly prograding.

The abovementioned stage of rapid progradation of the basin-margin clinoforms ended as clinoforms attained the deeper water reaches of the basin (Fig. 16). Clinoform progradation rate evidently slowed and their height increased as they prograded into deeper part of the basin (>500 m) north of Umpqua Arch. Significant aggradation of the clinoform topsets occurred at this stage as frequent transgressive–regressive shelf cycles developed on the topsets of the younger clinothems (stratigraphically higher parts of Tyee Forearc Succession) in southern Tyee Forearc Basin. With increasing height of the clinoforms (~500 m) well organized, large deepwater channels developed on the clinoform slopes in the central Tyee outcrop area. These provided large scale conduits for coarse clastics to reach the basin floor, forming thick successions of sandy basin-floor fans. The large slope-channel outcrops in the central Tyee Forearc Basin and the thick (estimated 2000 m) deep-sea fan deposits exposed in northern Tyee Forearc Basin formed at this stage.

5. Discussion

5.1. Evidence of changing dominant shoreline processes

The evolution of the Tyee Forearc Basin-margin as described in the previous section was accompanied by major changes in the configuration of Tyee shelf as evidenced by the change in dominant shoreline processes recorded from shallow marine deposits of southern and central Tyee Forearc Basin. The lower-most part of the non-marine to shallow marine succession exposed in southern Tyee Forearc Basin is dominated by thick, amalgamated fluvial deposits that are overlain by a number of cycles (>10) with shallow-marine and non-marine components. The shallow-marine deposits within these cycles show distinct variation in character over time. The shallow-marine deposits within the stratigraphically lower cycles show strong tide influence. These shallow-marine deposits are dominated by thick heterolithic strata and cross-bedded sandstones that also record abundant marine trace fossils. The heterolithics contain thin mud-layers and mud draped current ripples that show bi-directionality in dominant current. The cross-stratified sandstones are characterized by bi-directional cross strata of varying foreset heights. These sandstones are usually sharp-based and they show evidence of erosion at their bases indicating that these sandstones represent channel deposits that were strongly influenced by tidal processes. The dominance of tidal channel deposits might be an indication of highly embayed character of Tyee coastline at this stage.

In contrast to the lower cycles, the shallow marine deposits within the stratigraphically higher cycles include significant amount of wave dominated shoreline deposits in addition to the tidally influenced deposits. The records of increasing wave influence include abundant wave-ripple and hummocky cross stratification. Indications of strong wave-influence have been observed from some of the shallow-marine deposits exposed in the central Tyee Forearc Basin, which can be correlated with the previously discussed uppermost cycles of southern Tyee Forearc Basin. These deposits include shorefaces (FA 9) and finer wave dominated shelf deposits (FA 8). The gradual increase in wave influence within the shallow-marine deposits of Tyee is likely to be an indication of establishment of a wide and open shelf at relatively mature stage of development of the sedimentary prism at the Tyee margin that replaced pre-existing highly embayed narrow shelf.

5.2. Variability of turbidite architecture

The Tyee Forearc Succession as a whole has a very thick and areally extensive deepwater component that also shows significant spatial and temporal variability. As discussed earlier under lithofacies types and lithofacies associations (Tables 2 and 3) the three major architectural classes of sandy turbidite deposits observed within the Tyee Forearc Succession are (1) unconfined sandy slope turbidites or slope aprons, (2) sand-filled, large and very large-scale slope channel systems (including finer overbank deposits) and (3) unconfined sandy tubidite deposits that have been interpreted as the basin-floor fans.

The unconfined sandy slope turbidites, a key component of the early-stage margin in southern Tyee Forearc Basin, are exposed along the south-eastern and south-western boundary of the Tyee outcrop area and they directly (and unconformably) overlie the older siltstones of the Umpqua Group (Figs. 11b and 13a). These turbidite sandstones are characterized by overall tabular nature, absence of large-scale channelized erosion at their bases (as opposed to the slope channel-fills), evidence of slope instability in the form of large slump deposits (as opposed to the deepwater fans) and the presence of scattered extra-basinal pebbles. The latter suggest sediment transport to deep water directly from feeder rivers. This conclusion is based on two observations — a) the fluvial deposits are the only other deposits within the Tyee Forearc Succession where significant amounts of extra-basinal pebbles occur, and b) the slope-apron deposits in the southern Tyee Forearc Basin are directly overlain by thick fluvial deposits. The unconfined sandy slope turbidite deposits are restricted to the southernmost Tyee Forearc Basin, south of the Umpqua Arch, an interpreted shallow sub-basin that rapidly accumulated sediments in the earliest stage of the Tyee Forearc Basin-filling process. The unconfined turbidite deposits described above formed as the foresets of the small early-stage clinoforms that prograded across the southern Tyee Forearc Basin. At this stage, these thick sandy turbidite lobes simply dominated the foresets of the small clinoforms and continued to merge downbasin into basin-floor turbidites without significant incisions (Fig. 16a). These early unconfined slope-turbidite deposits linked directly with the fluvial sediment source, so that the basin-margin morphologically resembled a set of giant, turbidite-fronted deltas. Nearest modern analogies might be with fjord deltas that pass quickly to deep water turbidite systems without much intervening shallow-marine storage (Prior and Bornhold, 1988, 1989). These morphological characteristics of early-stage Tyee margin, resembling large turbidite-fronted deltas, are possibly the features highlighted in the 'submarine ramp' model of Heller and Dickinson (1985). However, they are not representative of the later history of Tyee Forearc Basin infill.

Abundant sandy slope-channel-fills are exposed in central Tyee Forearc Basin (Figs. 7a and 11b). At least six partly exposed deepwater channel systems were identified in this area. Outcrop information indicates a range of variability in channel width, degree of incision, degree of sand amalgamation, and stacking pattern of individual channel elements. These channel systems have width ranging from few 100 s of m to few km. The channel-systems are made of laterally and vertically stacked channel elements that are represented by 10 m to 25 m thick amalgamated sandstone bodies. The channel elements show lateral facies variation, from amalgamated sandstones to thick-bedded/medium-bedded sandstones interbedded with thin mudstone layers, within few 100 s of m. The estimated combined sand-body thickness for a channel system ranges from 60 m to >100 m. Recorded visible erosional relief associated with channel bases ranges from 10 m to few 10 s of m. The sandy slope channel-fills are encased within the extensive muddy slope deposits of central Tyee Forearc Basin that belong to the Elkton Formation or the Hubbard Creek member of Tyee Formation. These slope-channels were mostly formed at the second stage of basin development except those exposed in east-central Tyee Forearc Basin (north of Umpqua Arch between Elkton & Sutherlin; Fig. 11a). At the second and main stage of Tyee Forearc Basin infill the clinoform slopes across the length of the Tyee margin had become >500 m high and ~10 km long, a fairly typical shelf margin supplied by repeatedly regressing shorelines that delivered sediment to the shelf edge and into the large channelized slope conduits. The thick sandy basin-floor sand succession in northern Tyee Forearc Basin was formed as a result of this sand bypass across the deepwater slope through the above-mentioned large slope channel systems.

The thick basin-floor fan succession of Tyee Forearc Basin, characterized by very thick, tabular, turbidite sandstone beds (FA 3), has formed mostly at the second stage of basin-filling when large-scale slope channels were actively supplying sediment to the Tyee Forearc Basin-floor. At this stage the orientation of the Tyee shelf edge was close to E–W (with reference to present day orientation of the Tyee Forearc Basin) and fans were prograding northwards (Fig. 16). The deepwater fan succession is notable for its very sand-rich character, remarkable areal extent and great thickness, at least locally. The fans formed in the deeper part of the Tyee Forearc Basin (north of Umpqua Arch) consequently are restricted to the central and northern Tyee Forearc Basin. The progradation of the fans was probably influenced by topographic features in the basin-floor that might have restricted north-west ward progradation. At later stage of basin-filling the shelf-edge orientation was closer to E–W and the basin-floor fans prograded northward as indicated by the paleo-current data as well as facies trends.

5.3. Contrasting clinoform geometry (or margin style) within Tyee Forearc Basin — causes and implications

The temporal change in height (<250 m to >500 m) and stacking pattern (highly progradational to relatively more aggradational) character of the basin-margin clinoforms observed within Tyee Forearc Basin-fill were either controlled entirely by the geometry of the basin or by a combination of basin configuration and change in subsidence rate. Published subsidence data from the Tyee Forearc Basin, however, does not show evidence of increase in the rate of basin subsidence in Early or Middle Eocene. A comparison between reconstructed dip-oriented cross sections through central Tyee Forearc Basin (Fig. 15b) and southern Tyee Forearc Basin (Fig. 15a) shows that the smaller early-stage clinoforms and their characteristic facies stacking pattern were well-developed in southern Tyee Forearc Basin but not clearly distinguishable in central Tyee Forearc Basin. It is likely that the development of these smaller clinoforms in the early basin-filling stage was restricted to the southern part of the Tyee Forearc Basin (south of Umpqua Arch) which was relatively shallow. In central Tyee Forearc Basin no evidence for early stage smaller clinoforms have been observed as, in central Tyee Forearc Basin the clinoforms were advancing into a deeper (>500 m) bathymetry. It is possible that the smaller clinoforms of southern Tyee Forearc Basin prograded north-west ward across the southern shallow sub-basin relatively rapidly as compared to the larger clinoforms in central Tyee Forearc Basin. As a result, probably a progressive change in shelf edge orientation over time (from SSW–NNE oriented shelf edge to E–W oriented shelf edge) took place (Fig. 16), which is consistent with the paleo-current data recorded from Tyee Forearc Basin. The paleo-current data from the exposed deepwater fans in the northern Tyee Forearc Basin, that were supplied by the large slope channels at the second stage of basin-fill development, consequently record a northward progradation (perpendicular to the E–W oriented shelf edge at the later stage).

The early-stage, smaller clinoforms of the Tyee Forearc Basin margin, with their steep topsets, narrow shelf and sheet turbidite dominated slopes are probably not unique to this basin. A similar combination of lithofacies can probably be expected in the earliest stage of sedimentary prism growth in other high-gradient tectonic margins with narrow shelves and short slopes.

5.4. Implications in understanding of forearc depositional systems

The Tyee Forearc Basin deposits exposed in the Coast Range of Oregon forms a relatively continuous belt of outcrops that include fluvial deposits, deltaic/coastline/shelf deposits, deepwater slope deposits, and sandy basin floor deposits and unlike many other ancient forearc deposits, are only gently deformed. Mapping and correlation of the clastic deposits of Tyee Forearc Basin from outcrop and limited subsurface data allowed construction of a depositional model, albeit interpretive, from a source-to-sink approach. The thick deepwater turbidites, which have been described from many ancient and modern forearc basins (Tokuhashi, 1989; Takashima et al., 2004; Trop, 2008), are well represented in the Tyee Forearc Succession, but unlike in many other ancient forearc basins, these can be related to a fluvial/coastal to shelf deposition system. The paleo-current data recorded from the Tyee Forearc Basin as well as the interpreted clinoformal geometry imply major sediment input perpendicular to the longitudinal axis of the basin (which is oriented north–south at its present orientation). This transverse terrestrial sediment input from the arc side of the forearc basin is a characteristic feature for these kinds of basins and has been recorded in other ancient forearc deposits (Trop, 2008). The lack of evidence of strong deformation within the exposed Tyee Forearc Basin deposits in the Coast Range area of Oregon is somewhat unusual for a forearc succession, but can be explained in view of the tectonic framework proposed by previous workers such as, Simpson and Cox (1977) and, Wells and Heller (1988). This tectonic model (Fig. 3b) states that the Tyee Forearc Basin was formed on an oceanic terrane that was accreted onto the North American Plate following an arrest in subduction along a pre-existing subduction zone. The deposits related to this older plate margin forms part of the Umpqua Group and are strongly deformed. Following the deactivation of this Early Eocene subduction zone and accretion of the oceanic terrane (Siletz River Volcanic Terrane), new subduction zone formed at the western margin of the accreted oceanic terrane. The location of this newly-formed subduction zone was approximately near the present-day outer shelf off the Oregon Coast. Offshore seismic profiles have shown indication of large scale deformation in the Eocene level below the present-day outer shelf (Snavely et al., 1980). The studied outcrop area in the Coast Range of Oregon represents relatively proximal part of the Tyee Forearc Basin that possibly escaped strong penetrative deformation related to forearc tectonics. The relatively undeformed character of the studied outcrops and the uncertainty associated with the basin-wide correlation precluded the possibility of understanding the influence of the Early to Middle Eocene tectonic movements, if any, on the sediment transport and storage within the studied part of the Tyee Forearc Basin. Better understanding of the effect of the tectonic movements on the sediment fairways and depocentres within the Tyee Forearc Basin is needed for a better applicability of the proposed depositional model in modeling forearc sedimentation in general.

6. Conclusions

The clinoformal geometry of the basin infill implies that the pre-existing stratigraphic divisions of the sedimentary succession of the Tyee Basin (Ryu, 2003), which placed the basin-floor deposits, the slope deposits, and the fluvial- to shelf deposits of the Tyee Basin in separate time stratigraphic units, is essentially a lithostratigraphic classification. The results of the present study indicate that the boundaries between these stratigraphic units (formations and members) are time-transgressive in nature. The relative positions of the various stratigraphic units of the Tyee Basin including the Tyee Mountain, Hubbard Creek, and Baughman members of the Tyee Formation, and the Elkton and Bateman formations, concluded from this study, are schematically shown in Fig. 17. Development of the sedimentary succession in Eocene Tyee Forearc Basin took place in two distinct stages that can be related to the gradual development of a shelf-slope sedimentary prism at this tectonically active margin. The two stages are characterized by distinct clinoform heights, facies development and facies stacking patterns,

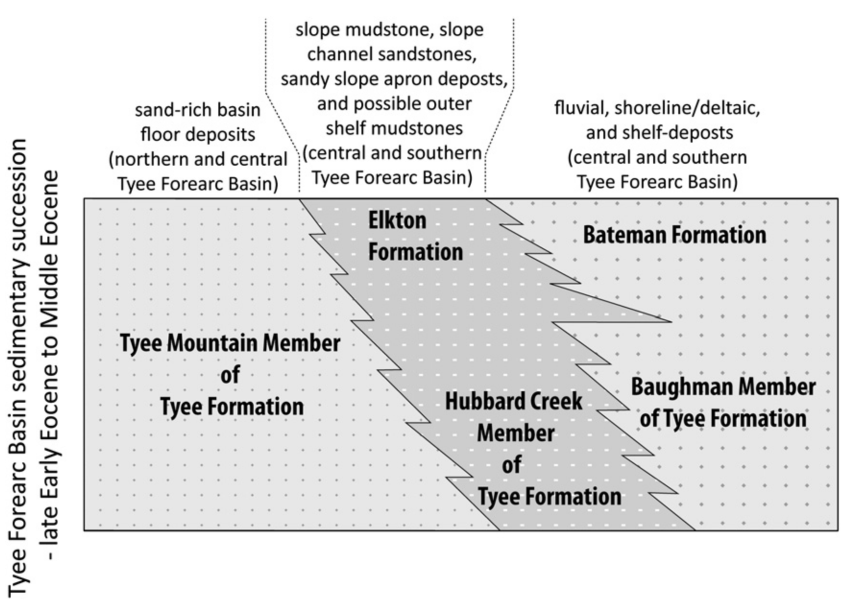

Fig. 17. Schematic diagram showing stratigraphic relationship between the lithostratigraphic units of the Tyee Forearc Basin.

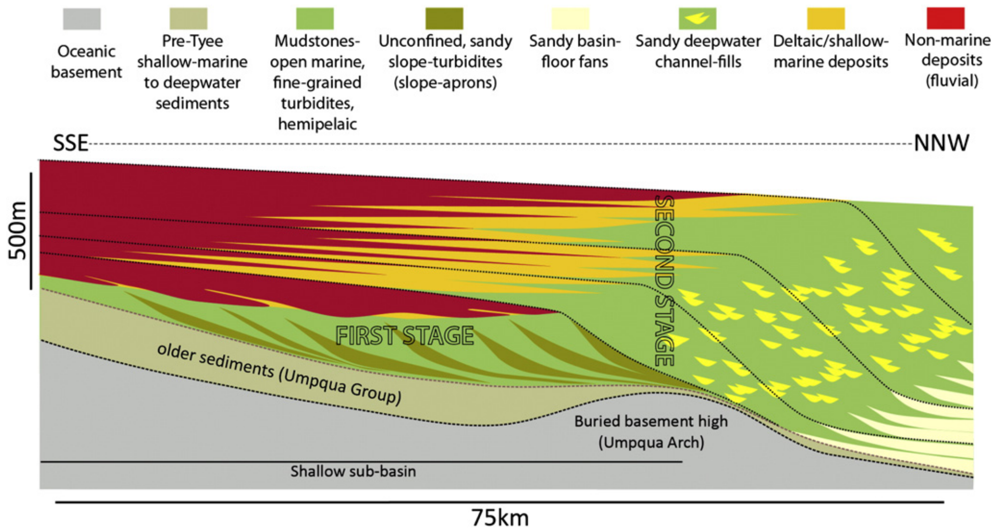

Fig. 18. Interpreted cross section through southern and central Tyee Forearc Basin showing two stages of development of the basin-fill, with distinct clinoform stacking patterns and facies development.

which were controlled to a great extent by the initial basin configuration. A slightly idealized basin-wide cross-section (Fig. 18) that combines reconstructed cross-sections from southern and central parts of the Tyee Forearc Basin (Fig. 15a,b) shows the varying clinoform stacking patterns, as well as the variation in facies characteristics corresponding to the two stages. The Tyee Forearc Basin was initially fed by multiple rivers from the east (or east–south-east) transverse to the basin axis, the majority of which supplied sediment to a shallow sub-basin in the southern part of Tyee Forearc Basin, south of the basement high known as Umpqua Arch. Because of the relatively shallow bathymetry of this sub-basin, the basin margin clinoforms building out into southern Tyee Forearc Basin were small (<250 m in height) whereas, the basin-margin clinoforms that later built out into the central Tyee Forearc Basin in front of the northern-most feeder rivers were larger (>500 m in height), as they were prograding into the deeper part of Tyee Forearc Basin north of Umpqua Arch. As a result, the basin-margin slope had variable length and height along strike (SSW–NNE in present orientation). The rate of progradation of the margin was also variable along strike, with rapid progradation into the shallow sub-basin in south and slower progradation into deeper water in central Tyee Forearc Basin, ultimately resulting in a change in orientation of the shelf-edge from initial SSW–NNE strike to final E–W strike.

The topsets of the small clinoforms that rapidly prograded across southern part of Tyee Forearc Basin, were dominated by fluvial strata, whereas the clinoform foresets were dominated by sandy unconfined turbidite deposits (sandy slope aprons). These smaller clinoforms (Fig. 18), characterize the initial stage of sedimentary prism development on the Tyee Forearc Basin margin. As these clinoforms prograded beyond the southern shallow sub-basin, approaching the deep basinal part of the Tyee forearc north of Umpqua Arch, the clinonoform height increased and the clinoforms became more aggradational. At this stage, which lasted thought the rest of the basin-filling process, repeated fluvio-deltaic cycles developed on the topsets of these larger clinoforms and large turbidite channels developed on the deepwater slopes that allowed significant bypass of the coarse clastics to the basin floor resulting in the accumulation of a very thick and extensive deepwater fan succession.

Acknowledgment

We would like to thank ExxonMobil for the financial support and for their continued interest in the study of the Tyee Basin. Additional support was provided by The Jackson School of Geosciences at The University of Texas at Austin and by AAPG grant in aid program. Our thanks go to our colleagues at the Dynamic Stratigraphy Group at The Jackson School of Geosciences for their assistance in parts of our fieldwork in Coast Range, Oregon. We would like to thank undergraduate field assistant Shane Lewis for his valuable assistance during the 2010 field season.

References

Bukry, D., Snavely Jr., P.D., 1988. Coccolith zonation for Paleogene strata in the Oregon Coast Range. In: Filewicz, M.V., Squires, R.L. (Eds.), Paleogene Stratigraphy, West Coast of North America: Pacific Section, Society of Economic Paleontologists and Mineralogists: West Coast Paleogene Symposium, 58, pp. 251–263.
Burgess, P.M., Steel, R., 2008. Stratigraphic forward modeling of basin-margin clinoform systems: implications for controls on topset and shelf width and timing of formation of shelf-edge deltas. Society of Economic Paleontologists and Mineralogists Special Publication 90, 35–45.
Carvajal, C.R., Steel, R.J., 2006. Thick turbidite successions from supply-dominated shelves during sea-level highstand. Geology 34 (8), 665–668.
Chan, M.A., Dott, R.H., 1983. Shelf and deep-sea sedimentation in Eocene fore-arc basin, western Oregon — fan or non-fan. AAPG Bulletin-American Association of Petroleum Geologists 67 (11), 2100–2116.
Duncan, R.A., 1982. A captured island chain in the Coast Range of Oregon and Washington. Journal of Geophysical Research 87 (NB13), 827–837.
Helland-Hansen, W., Steel, R.J., SÃ¸mme, T.O., 2012. Shelf genesis revisited. Journal of Sedimentary Research 82 (3), 133–148.
Heller, P.L., Dickinson, W.R., 1985. Submarine ramp model for delta-fed, sand-rich turbidite systems. AAPG Bulletin-American Association of Petroleum Geologists 69 (6), 960–976.
Heller, P., Peterman, Z.E., Shafiqullah, M., 1984. Isotopic provenance of sandstones from the displaced Tyee Formation, Oregon Coast Range. AAPG Bulletin-American Association of Petroleum Geologists 68 (4), 485–485.
Heller, P.L., Ryberg, P.T., 1983. Sedimentary record of subduction to fore-arc transition in the rotated Eocene basin of western Oregon. Geology 11 (7), 380–383.
Johannessen, E.P., Steel, R.J., 2005. Shelf-margin clinoforms and prediction of deepwater sands. Basin Research 17 (4), 521–550.
Lovell, J.P.B., 1969. Tyee Formation — a study of proximity in turbidites. Journal of Sedimentary Petrology 39 (3), 935–953.
Marcaillou, B., Collot, J.-Y., 2008. Chronostratigraphy and tectonic deformation of the North Ecuadorian–South Colombian offshore Manglares forearc basin. Marine Geology 255, 30–44.
Prior, D.B., Bornhold, B.D., 1988. Submarine morphology and processes of fjord fan deltas and related high-gradient systems: modern examples from British Columbia. In: Nemec, W., Steel, R.J. (Eds.), Fan Deltas: Sedimentology and Tectonic Settings. Blackie, London, pp. 125–143.
Prior, D.B., Bornhold, B.D., 1989. Submarine sedimentation on a developing Holocene fan delta. Sedimentology 36 (6), 1053–1076.
Roberts, C.W., Kucks, R.P., Hill, P.L., 2008. Oregon magnetic and gravity maps and data — a website for distribution of data. U.S. Geological Survey Data Series 355.
Ryu, I.C., 2003. Petrography, diagenesis and provenance of Eocene Tyee Basin sandstones, southern Oregon Coast Range: new view from sequence stratigraphy. Island Arc 12 (4), 398–410.

Ryu, I.C., Niem, A.R., 1999. Sandstone diagenesis, reservoir potential, and sequence stratigraphy of the Eocene Tyee basin, Oregon. Journal of Sedimentary Research 69 (2), 384–393.

Ryu, I.C., Niem, A.R., Niem, W.A., 1992. Schematic fence diagram of the southern Tyee basin, Oregon Coast Range, showing stratigraphic relationships of exploration wells to surface measured sections. Oregon Dept. of Geology and Mineral Industries Oil and Gas Investigation, 18 . (29 pp.).

Simpson, R.W., Cox, A., 1977. Paleomagnetic evidence for tectonic rotation of Oregon Coast Range. Geology 5 (10), 585–589.

Snavely Jr., P.D., Wagner, H.C., 1963. Tertiary geologic history of western Oregon and Washington.

Snavely Jr., P.D., Wagner, H.C., McLeod, N.S., 1964. Rhythmic-bedded eugeosynclinal deposits of the Tyee Formation, Oregon Coast Range. Kansas Geological Survey Bulletin 169, 461–480.

Snavely Jr., P.D., Wagner, H.C., Lander, D.L., 1980. Interpretation of the Cenozoic geologic history, central Oregon continental margin: Cross-section summary. Geological Society of America Bulletin 91, 143–146.

Takashima, R., et al., 2004. Geology and stratigraphy of forearc basin sediments in Hokkaido, Japan; Cretaceous environmental events on the north-west Pacific margin. Cretaceous Research 25 (3), 365–390.

Tokuhashi, S., 1989. Two Stages of Submarine Fan Sedimentation in an Ancient Forearc Basin, Central Japan Advances in Earth and Planetary Sciences. Terra Sci. Publ. Co., Tokyo, Japan, Japan, pp. 439–468.

Trop, J.M., 2008. Latest Cretaceous forearc basin development along an accretionary convergent margin: South-central Alaska. Geological Society of America Bulletin 120, 207–224.

Wells, R.E. et al., 2000. Geologic Map and Database of the Roseburg $30\times60'$ Quadrangle, Douglas and Coos Counties, Oregon U.S. Geological Survey Open-File Report 00-376.

Wells, R.E., Heller, P.L., 1988. The relative contribution of accretion, shear, and extension to Cenozoic tectonic rotation in the Pacific Northwest. Geological Society of America Bulletin 100 (3), 325–338.