Tide-dominated estuarine facies in the Hollin and Napo ("T" and "U") formations (Cretaceous), Sacha field, Oriente Basin, Ecuador: Discussion

Roger Higgs*

INTRODUCTION

The article by Shanmugam et al. (2000) is a welcome addition to the scant sedimentological literature on the Oriente Basin and its continuation in Colombia, the Putumayo Basin (Higgs, 1997a). Shanmugam et al. (2000) reinterpreted the Hollín and Napo T-U sands as tide-dominated estuarine deposits, rejecting a previous deltaic model. Neither model, however, accords with the stated lack of evidence for subaerial emergence. An alternative, tidal shelf interpretation is promoted here, and petroleum reservoir implications discussed. Also, although Shanmugam et al. (2000) did not report any sequence boundaries, their data suggest that angular (tectonic) sequence boundaries occur at the base of the A and B limestones, signifying possible incised valleys cutting into the U and T sands, again important for oil exploration.

*Geoclastica Ltd, 2a Harbord Road, Oxford, England OX2 8LQ; rogerhiggs@geoclastica.com.

Manuscript received June 27, 2000; final acceptance May 16, 2001

ARGUMENTS FOR SHELF, NOT ESTUARINE, DEPOSITION

Lack of Emergence Indicators

The 516 ft (157 m) of cores from seven wells examined by Shanmugam et al. (2000) show a simple facies association of shales, heterolithics, and cross-bedded sands. "[N]o evidence for subaerial exposure" exists (Shanmugam et al., 2000, p. 674); for example, "rooting is lacking" (Shanmugam et al., 2000, p. 660) and no coal beds, paleosoils, or desiccation cracks were reported. Sparse interpreted marsh deposits (<1% of one 58 ft core) (Shanmugam et al., 2000, table 2) are based on nondiagnostic interpretation criteria, that is, sandstone with "intervals of concentrated carbonaceous fragments . . . may be interpreted as a marsh environment" (Shanmugam et al., 2000, p. 660). Alternatively, such plant-flake concentrations could occur on a shelf because of tidal-current segregation of particles. An interpreted "fluvial channel" is based solely on "cross-stratification and basal lags" (Shanmugam et al., 2000, p. 656), both of which can also apply to submarine tidal bars (e.g., Stride et al., 1982, figure 5.22; Dalrymple, 1992, figure 29C).

The same facies association and absence or scarcity of emergence indicators characterizes the Hollín and Napo T-U units in other Oriente Basin fields besides Sacha field (Alvarado et al., 1982; White et al., 1995) and the contiguous Caballos and Villeta T-U intervals in the adjacent Putumayo Basin (Cáceres and Teatín, 1985; Amaya, 1996; Amaya and Centanaro, 1997; R. Higgs, 1998, unpublished data).

The lack of evidence for emergence is difficult to reconcile with an estuarine or deltaic interpretation, because in humid climates (tropical paleolatitude [Smith et al., 1980]), marshes comprise a large areal percentage of the delta plain or estuary (30–80%) (e.g., Shanmugam et al., 2000, figure 24a); therefore, deltaic or estuarine successions should correspondingly contain a large proportion of marsh facies (rooted coal beds; paleosoils), unless one appeals to either of two special cases: (1) ravinement has removed all of the marsh facies, which seems overly fortuitous; or (2) the study area is small enough to fit entirely within the subaqueous delta slope or central/outer estuary. The latter explanation is not applicable: Sacha field itself is nearly small enough (25 × 5 km) (Canfield, 1991) to fit inside the Oosterschelde estuary modern analog of Shanmugam et al. (2000, p. 672; "mouth . . . 7.4 km wide"), but the overall Hollín-Napo T-U facies association continues laterally for more than 100 km in all directions, with no known breaks (see following sections). A second modern analog given by Shanmugam et al. (2000, p. 673), the "Bristol Channel estuary" ("mouth . . . 38.8 km wide,"), is not an estuary but a shelf seaway, narrowing eastward to the Severn estuary.

Lack of Intertidal Indicators

Intertidal flat facies should also be conspicuous in any estuarine facies association (e.g., Shanmugam et al., 2000, figure 24a). Shanmugam et al. (2000), however, reported no diagnostic intertidal sedimentary structures, such as desiccation cracks (Dalrymple, 1992), wrinkle marks, ladderback ripples, or flat-topped ripples (Mángano and Buatois, 1997).

Great Areal Extent

The characteristic Hollín-Caballos and Napo-Villeta T-U facies association (see previous sections) extends for at least 150 km north to south (Oriente-Putumayo Basin). About 200 km farther north, across the Garzón mountains, the same Caballos facies reappear in the Upper Magdalena Basin (Corrigan, 1967; Flórez and Carrillo, 1994; Renzoni, 1994). The east-west extent is at least 100 km in the Oriente Basin (e.g., Dashwood and Abbotts, 1990, figure 5 isopach maps). This great areal extent is clearly more compatible with a shelf than with estuaries or deltas. The depositional environment was a broad, north-south marine shelf stretching from Bolivia to Venezuela in the Aptian–Santonian, according to Pindell and Tabbutt (1995, figures 4, 5). According to Corrigan (1967, p. 231), "The Caballos and the Une represent the shelf facies of the great marine transgression in Aptian–Albian time," expressed on the eustatic chart of Haq et al. (1988).

Lack of Evidence for Incision (Incised Valleys)

An incised-valley (fluvial and estuarine) interpretation, applied to parts of the Hollín and Napo T-U intervals by White et al. (1995) and other workers, was rejected by Shanmugam et al. (2000) because seismic profiles and well-correlation panels at Sacha field suggest that incision is absent or minor below and within the Hollín and Napo formations. A lack of incised valleys, however, would also condemn the estuarine model of Shanmugam et al. (2000), because estuaries occupy incised valleys by definition (Dalrymple et al., 1992).

Given the angular unconformity at the base of the Hollín Formation (Shanmugam et al., 2000), incised valleys might occur on that surface, possibly explaining lateral thickness variations in the lower Hollín–lower Caballos interval (White et al., 1995; Amaya, 1996). Such incised valleys would be expected to contain fluvial and/or estuarine deposits (Van Wagoner et al., 1990) and to be confined to the lower Hollín-Caballos. In contrast, virtually the entire Hollín-Caballos interval was interpreted as fluvial and estuarine by White et al. (1995) and Amaya (1996).

Limited Ichnofauna and Microfauna

The generally low-diversity ichnofauna of the Hollín-Caballos and Napo-Villeta T-U intervals (Flórez and Carrillo, 1994; White et al., 1995; Amaya, 1996; Amaya and Centanaro, 1997; R. Higgs, 1998, unpublished data; Shanmugam et al., 2000) is consistent with the tropical shelf interpretation proposed here. In the tropics, inflowing muddy rivers cause high turbidity (suspended clay) in the shelf waters, detrimental to suspension-feeding burrowers (Buatois et al., 1997). In contrast, the limited ichnofauna was attributed to reduced salinity or rapid sedimentation by Shanmugam et al. (2000, p. 659, 661).

Planktonic foraminifera are also scarce or absent in these intervals (Tschopp, 1953; Alvarado et al., 1982; Renzoni, 1994; White et al., 1995), typical of inner-shelf deposits (Emery and Myers, 1996, p. 93 and figure 6.2), reflecting high turbidity (Stainforth, 1948; Ho, 1978). This dual scarcity of ichnogenera and planktonic forams causes shelf deposits to be misinterpreted as coastal in many basins worldwide, with serious consequences for economic oil extraction (e.g., Higgs, 1996, 1997b, 1999).

Environmental Summary

Diverse lines of evidence support deposition of the Hollín-Caballos and Napo-Villeta T-U intervals on a tide-influenced shelf. The facies association is remarkably similar to that of other formations interpreted as tidal-shelf deposits (e.g., Anderton, 1976; Higgs, 1996) and to modern tidal-shelf deposits (Belderson et al., 1982; Stride et al., 1982). A shallow-marine interpretation is already well established for the Hollín (Baldock, 1982) and Caballos formations (Corrigan, 1967; Govea and Aguilera, 1980; Cáceres and Teatín, 1985; Cooper et al., 1995, figure 5), although an estuarine model was recently proposed for the Caballos (Amaya, 1996; Amaya and Centanaro, 1997; Ramon and Pavas, 1999), similar to the Hollín (Shanmugam et al., 2000).

IMPLICATIONS FOR RESERVOIR SAND GEOMETRY

General

Of particular significance for petroleum exploration and development, Shanmugam et al. (2000) pointed out that their model of an east-west estuary predicts east-west subtidal sand bars, whereas, they contend, the previous west-facing delta model predicts north-south distributary mouth bars. (The delta model would also predict east-west distributary channels.) In contrast, the shelf interpretation proposed here implies much larger sand bodies (sand sheets; see the following section), in addition to bars, and lower predictability of bar orientation.

Sand-Body Geometry

Sand bodies in the Hollín and Napo formations (and their Colombian counterparts) are predicted to be sheets and/or bars (synonymous with sand banks or ridges) by analogy with (1) the modern, tide-dominated northwest European shelf (Belderson et al., 1982; Stride et al., 1982; Belderson, 1986) and (2) carefully studied ancient analogs (e.g., Anderton, 1976; Hobday and Tankard, 1978; Houbolt, 1982; Houthuys and Gullentops, 1988; Banerjee, 1989). Modern bars are typically 10–50 km long, 1–3 km wide, 1–20 km apart, and 5–50 m thick at the axis, whereas sheets are 50–400 km long, 10–50 km wide, and 5–12 m thick (Belderson et al., 1982; Stride et al., 1982). Bar and sheet thickness can be reduced erosively by storms (Anderton, 1976; Belderson et al., 1982; Stride et al., 1982) and by tsunami waves. Bars and sheets can amalgamate vertically to form thicker, composite sand bodies of more complex architecture. Contemporaneous growth of sea-floor anticlines (see following sections) may have localized sand-body development (White et al., 1995; Nielsen et al., 1999).

Sand-Body Orientation

Unlike subaqueous bars in estuaries or delta fronts, the orientation of tidal-shelf bars is not necessarily constrained by the orientation of the coast. Modern shelf bars in northwest Europe are slightly oblique to the direction of net sand transport (Kenyon et al., 1981; Belderson et al., 1982), which itself depends on the tidal-current circulation and velocity-asymmetry pattern. Thus, subsurface prediction of shelf sand-bar orientation requires detailed knowledge of paleogeography.

SEQUENCE STRATIGRAPHY

The Hollín-Caballos and Napo-Villeta T-U sands are respectively overlain by the C, B, and A limestones over much of the Oriente-Putumayo Basin (Cáceres and Teatín, 1985; Govea and Aguilera, 1985; Dashwood and Abbotts, 1990, figure 4). The A and B limestones were interpreted as "regional transgressive" deposits by Shanmugam et al. (2000, p. 671), although not studied by them. In my experience, these so-called limestone units are actually interbedded shale and argillaceous limestone, the latter comprising concretionary bands and nodules, formed of calcite-cemented shelly siliciclastic mud. The argillaceous composition produces a high gamma-ray response (Shanmugam et al., 2000, figures 3, 23, 26). The concretion-precursor shelly mud may have resembled the "skeletal wackestone" described by Shanmugam et al. (2000, p. 663; also figure 19), which occurs as thin beds in Hollín and Napo T-U shales (their facies 7). These thin shelly beds were possibly deposited as calcarenite and calcirudite storm beds, which were then burrow-mixed with the background siliciclastic mud, masking bed boundaries. Because of the mud matrix, the A, B, and C limestones have minimal primary-porosity potential but are locally capable of producing oil from fractures.

No sequence boundaries were reported in the Hollín or Napo formations by Shanmugam et al. (2000), except the basal unconformity. In a correlation panel from Sacha field, however, the T and U sands vary considerably in thickness, in marked contrast to the overlying B and A limestones and the underlying shale unit, which are relatively tabular (Shanmugam et al., 2000, figure 26). This geometry suggests that the limestones overlie angular unconformities formed by folding and erosional planation prior to limestone deposition. Similarly, correlation panels at Coca-Payamino and Gacela fields (location shown in Shanmugam et al., 2000, figure 1) show a tabular limestone/marl unit (C-equivalent) capping a nontabular upper Hollín interval (White et al., 1995, figures 15, 16), suggesting a sub-C angular sequence boundary.

The inferred sublimestone unconformities imply intermittent tectonism during Hollín-Napo deposition, in agreement with (1) seismic profiles showing syn-Napo growth of Oriente Basin anticlines (Balkwill et al., 1995, especially figure 7) and (2) interpreted synsedimentary fault control of T and U sand thicknesses in Libertador field (Lozada et al., 1985; field location shown in Shanmugam et al., 2000, figure 1). The tectonic pulses were probably compressive (Balkwill et al., 1995) or transpressive (Baby et al., 1998), causing subtle basement-block uplifts in an "embryonic foreland basin" (Balkwill et al., 1995, p. 568), related to eastward subduction below an active arc to the west (Macellari, 1988). (Contrast the passive-margin interpretation of Pindell and Tabbutt [1995, figure 4] and White et al. [1995].) Each uplift episode caused brief emergence of the Hollín-Napo shelf or of small islands localized on growing anticlines. Marine transgression then beveled the highs by ravinement, and shelf deposition resumed. The switch from siliciclastic tidal sands before each uplift episode to calcarenite storm beds after each uplift episode reflects a change in paleogeography and a decrease in terrigenous sand supply, the latter reflecting rising relative sea level and/or perhaps a climate change resulting in increased aridity. A climatic-tectonic genetic link may have operated, whereby a large intraforeland tectonic block east of the Oriente-Putumayo Basin was uplifted synchronously with, but much higher than, the Oriente-Putumayo anticlines, each time producing a rain shadow (assuming easterly prevailing equatorial winds) whose effectiveness progressively decreased because of erosional lowering. A candidate for this rain-shadow maker is the Chiribiquete massif of Colombia (INGEOMINAS, 1988), a range of hills up to 1000 m high, composed of Paleozoic rocks, and oriented north-south, parallel with the anticlines of the Oriente-Putumayo Basin.

The inferred sublimestone sequence boundaries raise the possibility of an associated incised-valley exploration play. The incised valleys would contain fluvial and/or estuarine facies (Van Wagoner et al., 1990), cutting into the Hollín-Caballos and Napo-Villeta T-U shelf sands.

Unrelated to these sublimestone tectonic sequence boundaries, White et al. (1995, p. 585 and figure 12) proposed three eustatic sequence boundaries, at the base of the upper Hollín and the Napo T and U intervals, corresponding to the Haq et al. (1988) eustatic falls at 98, 94, and 90 Ma. These are type 1 sequence boundaries, and the upper Hollín, T, and U are incised-valley fills, according to White et al. (1995). Type 2, however, is more likely, given the evidence for shelf, rather than fluvial or estuarine deposition of these units (see previous discussion). The commonly sharp base of the T and U sands (e.g., White et al., 1995, figure 9; Shanmugam et al., 2000, figures 23, 26) is consistent with eustatically forced regressions emplacing inner-shelf sands (bars or sheets) on outer-shelf muds (Plint, 1988). Failure of each eustatic lowering to expose the shelf indicates that the subsidence rate exceeded the (nonglacial) rate of eustatic fall, consistent with a tectonically active foreland basin.

REFERENCES CITED

Alvarado, G., G. Bonilla, G. G. de Rojas, and R. Z. de Arroyo, 1982, Análisis sedimentológico de la zona Arenisca Napo "T" en la Cuenca del Napo: I Simposio Bolivariano de la Exploración Petrolera en Las Cuencas Subandinas, Bogotá, Colombia, Memorias, v. 2, unpaginated.

Amaya, C. A., 1996, Architecture of estuarine reservoirs of the Cretaceous Caballos Formation, Orito field, Putumayo Basin, Colombia: Master's thesis, University of Texas at Austin, 105 p.

Amaya, C. A., and J. Centanaro, 1997, Ambiente deposicional y modelamiento del yacimiento Caballos en el Campo Orito, Cuenca Putumayo: VI Simposio Bolivariano de la Exploración Petrolera en Las Cuencas Subandinas, Cartagena, Colombia, Memorias, v. 2, p. 26–29.

Anderton, R., 1976, Tidal-shelf sedimentation: an example from the Scottish Dalradian: Sedimentology, v. 23, p. 429–458.

Baby, P., M. Rivadeneira, C. Bernal, F. Christophoul, C. Davila, M. Galarraga, R. Marocco, A. Valdez, and J. Vega, 1998, Structural style and timing of hydrocarbon entrapments in the Ecuadorian Oriente Basin (abs.): AAPG Bulletin, v. 82, p. 1889.

Baldock, J. W., 1982, Geology of Ecuador (explanatory bulletin of the national geological map of the Republic of Ecuador): Ministerio de Recursos Naturales y Energéticos, Dirección General de Geología y Minas, Quito, Ecuador, 59 p.

Balkwill, H. R., G. Rodrigue, F. I. Paredes, and J. P. Almeida, 1995, Northern part of Oriente Basin, Ecuador: reflection seismic expression of structures, *in* A. J. Tankard, R. Suárez, and H. J. Welsink, eds., Petroleum basins of South America: AAPG Memoir 62, p. 559–571.

Banerjee, I., 1989, Tidal sand sheet origin of the transgressive Basal Colorado Sandstone (Albian): a subsurface study of the Cessford field, southern Alberta: Bulletin of Canadian Petroleum Geology, v. 37, p. 1–17.

Belderson, R. H., 1986, Offshore tidal and non-tidal sand ridges and sheets: differences in morphology and hydrodynamic setting, *in* R. J. Knight and J. R. McLean, eds., Shelf sands and sandstones: Canadian Society of Petroleum Geologists Memoir 11, p. 293–301.

Belderson, R. H., M. A. Johnson, and N. H. Kenyon, 1982, Bedforms, *in* A. H. Stride, ed., Offshore tidal sands: London, Chapman and Hall, p. 27–57.

Buatois, L. A., M. G. Mángano, C. G. Maples, and W. P. Lanier, 1997, The paradox of nonmarine ichnofaunas in tidal rhythmites: integrating sedimentologic and ichnologic data from the Late Carboniferous of eastern Kansas, USA: Palaios, v. 12, p. 467–481.
Cáceres, H., and P. Teatín, 1985, Cuenca del Putumayo, provincia petrolera meridional de Colombia: II Simposio Bolivariano de la Exploración Petrolera en las Cuencas Subandinas, Bogotá, Colombia, Memorias, v. 1, 80 p.
Canfield, R. W., 1991, Sacha field, Ecuador, *in* N. H. Foster and E. A. Beaumont, eds., Structural traps V: AAPG Treatise of Petroleum Geology, Atlas of Oil and Gas Fields, p. 285–305.
Cooper, M. A., et al., 1995, Basin development and tectonic history of the Llanos Basin, Eastern Cordillera, and middle Magdalena Valley, Colombia: AAPG Bulletin, v. 79, p. 1421–1443.
Corrigan, H. T., 1967, The geology of the Upper Magdalena Basin (northern portion), *in* Colombian Society of Petroleum Geologists and Geophysicists, geological field trips Colombia, 1959–1978: Bogotá, Ediciones Geotec Ltda., p. 221–251.
Dalrymple, R. W., 1992, Tidal depositional systems, *in* R. G. Walker and N. P. James, eds., Facies models: response to sea level change: Geological Association of Canada, p. 195–218.
Dalrymple, R. W., B. A. Zaitlin, and R. Boyd, 1992, Estuarine facies models: conceptual basis and stratigraphic implications: Journal of Sedimentary Petrology, v. 62, p. 1130–1146.
Dashwood, M. F., and I. L. Abbotts, 1990, Aspects of the petroleum geology of the Oriente Basin, Ecuador, *in* J. Brooks, ed., Classic petroleum provinces: Geological Society Special Publication 50, p. 89–117.
Emery, D., and K. Myers, 1996, Sequence stratigraphy: Oxford, Blackwell Science, 297 p.
Flórez, J. M., and G. A. Carrillo, 1994, Estratigrafía de la sucesión litológica basal del Cretacico del Valle Superior del Magdalena, *in* F. Etayo Serna, ed., Estudios geológicos del Valle Superior del Magdalena: Bogotá, Universidad Nacional de Colombia, trabajo II, 26 p.
Govea, C., and H. Aguilera, 1980, Geología de la Cuenca del Putumayo: Boletín Geológico, Universidad Industrial de Santander, Bucaramanga, v. 14, p. 45–71.
Govea, C., and H. Aguilera, 1985, Cuencas sedimentarias de Colombia: II Simposio Bolivariano de la Exploración Petrolera en las Cuencas Subandinas, Bogotá, Colombia, Memorias, v. 2, 93 p.
Haq, B. U., J. Hardenbol, and P. R. Vail, 1988, Mesozoic and cenozoic chronostratigraphy and cycles of sea-level change, *in* C. K. Wilgus, B. S. Hastings, C. G. St. C. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., Sea-level changes: an integrated approach: SEPM Special Publication 42, p. 71–108.
Higgs, R., 1996, A new facies model for the Misoa Formation (Eocene), Venezuela's main oil reservoir: Journal of Petroleum Geology, v. 19, p. 249–269.
Higgs, R., 1997a, Book review, Petroleum basins of South America, ed. by A. J. Tankard, R. Suárez Soruco and H. J. Welsink: Basin Research, v. 9, p. 87–88.
Higgs, R., 1997b, Sequence stratigraphy and sedimentology of the Misoa Formation (Eocene), Lake Maracaibo, Venezuela: I Congreso Latinoamericano de Sedimentología, Sociedad Venezolana de Geólogos, Margarita, Venezuela, Memorias, v. 1, p. 325–333.
Higgs, R., 1999, Gravity anomalies, subsidence history and the tectonic evolution of the Malay and Penyu basins (offshore Peninsula Malaysia): discussion: Basin Research, v. 11, p. 285–290.
Ho, K. F., 1978, Stratigraphic framework for oil exploration in Sarawak: Geological Society of Malaysia Bulletin, v. 10, p. 1–13.
Hobday, D. K., and A. J. Tankard, 1978, Transgressive-barrier and shallow-shelf interpretation of the lower Paleozoic Peninsula Formation, South Africa: Geological Society of America Bulletin, v. 89, p. 1733–1744.
Houbolt, J. J. H. C., 1982, A comparison of recent shallow marine tidal sand ridges with Miocene sand ridges in Belgium, *in* R. A. Scrutton and M. Talwani, eds., The ocean floor: Chichester, John Wiley, p. 69–80.
Houthuys, R., and F. Gullentops, 1988, The Vlierzele Sands (Eocene, Belgium): a tidal ridge system, *in* P. L. de Boer, A. van Gelder, and S. D. Nio, eds., Tide-influenced sedimentary environments and facies: Boston, D. Reidel, p. 139–152.
INGEOMINAS, 1988, Mapa geológico de Colombia: Bogotá, Instituto Nacional de Investigaciones Geológico-Mineras, Ministerio de Minas y Energía, scale 1:1,500,000, 71 p.
Kenyon, N. H., R. H. Belderson, A. H. Stride, and M. A. Johnson, 1981, Offshore tidal sand banks as indicators of net sand transport and as potential deposits, *in* S.-D. Nio, R. T. E. Schüttenhelm, and Tj. C. E. van Weering, eds., Holocene marine sedimentation in the North Sea Basin: International Association of Sedimentologists Special Publication 5, p. 257–268.
Lozada, T., P. Endara, and C. Cordero, 1985, Exploración y desarrollo del Campo Libertador: II Simposio Bolivariano de la Exploración Petrolera en las Cuencas Subandinas, Bogotá, Colombia, Memorias, v. 1, 8 p.
Macellari, C. E., 1988, Cretaceous paleogeography and depositional cycles of western South America: Journal of South American Earth Sciences, v. 1, p. 373–418.
Mángano, M. G., and L. A. Buatois, 1997, Análisis icnológico comparativo de planicies mareales Carboníferas del este de Kansas: I Congreso Latinoamericano de Sedimentología, Sociedad Venezolana de Geólogos, Margarita, Venezuela, Memorias, v. 2, p. 1–6.
Nielsen, K. S., C. Schroder-Adams, and D. Leckie, 1999, Drill the flanks, not the crest: structural influence on shelf sand reservoirs (abs.): AAPG Annual Meeting Program and Abstracts, p. A100–A101.
Pindell, J. L., and K. D. Tabbutt, 1995, Mesozoic–Cenozoic Andean paleogeography and regional controls on hydrocarbon systems, *in* A. J. Tankard, R. Suárez, and H. J. Welsink, eds., Petroleum basins of South America: AAPG Memoir 62, p. 101–128.
Plint, A. G., 1988, Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta: their relationship to relative changes in sea level, *in* C. K. Wilgus, B. S. Hastings, C. G. St. C. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., Sea-level changes: an integrated approach: SEPM Special Publication 42, p. 357–370.
Ramon, J. C., and J. Pavas, 1999, Sedimentology and sequence stratigraphy of the Caballos Formation, San Francisco field, Upper Magdalena Valley (abs.): AAPG Annual Meeting Program and Abstracts, p. A113–A114.
Renzoni, G., 1994, Caballos (Formación): INGEOMINAS, Instituto de Investigaciones en Geociencias, Minería y Química, Catalogo de las Unidades Estratigráficas de Colombia, Bogotá, 35 p.
Shanmugam, G., M. Poffenberger, and J. Toro Alava, 2000, Tide-dominated estuarine facies in the Hollin and Napo ("T" and "U") formations (Cretaceous), Sacha field, Oriente Basin, Ecuador: AAPG Bulletin, v. 84, p. 652–682.
Smith, A. G., A. M. Hurley, and J. C. Briden, 1980, Phanerozoic paleocontinental world maps: Cambridge, Cambridge University Press, 98 p.
Stainforth, R. M., 1948, Description, correlation, and paleoecology of Tertiary Cipero Marl Formation, Trinidad, B.W.I.: AAPG Bulletin, v. 32, p. 1292–1330.
Stride, A. H., R. H. Belderson, N. H. Kenyon, and M. A. Johnson, 1982, Offshore tidal deposits: sand sheet and sand bank facies,

in A. H. Stride, ed., Offshore tidal sands: London, Chapman and Hall, p. 95–125.
Tschopp, H. J., 1953, Oil explorations in the Oriente of Ecuador: AAPG Bulletin, v. 37, p. 2303–2347.
Van Wagoner, J. C., R. M. Mitchum, K. M. Campion, and V. D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high resolution correlation of time and facies: AAPG Methods in Exploration Series 7, 55 p.
White, H. J., R. A. Skopec, F. A. Ramirez, J. A. Rodas, and G. Bonilla, 1995, Reservoir characterization of the Hollin and Napo formations, western Oriente Basin, Ecuador, *in* A. J. Tankard, R. Suárez and H. J. Welsink, eds., Petroleum basins of South America: AAPG Memoir 62, p. 573–596.

Tide-dominated estuarine facies in the Hollin and Napo ("T" and "U") formations (Cretaceous), Sacha field, Oriente Basin, Ecuador: Reply

G. Shanmugam* and M. Poffenberger**

INTRODUCTION

We conclude at the outset that Higgs's (2002) discussion is not based on his examination of core and outcrop of the Hollin and Napo formations in the Sacha field in Ecuador that we used (Shanmugam et al., 2000). Our conclusion is based on (1) the lack of any reference to his own core or outcrop study of the Sacha field, (2) the lack of specific details of core descriptions from the Sacha field, and (3) the lack of any photographic documentation of sedimentary features from the Sacha field in support of his tidal shelf model. A rigorous photographic documentation of sedimentological features is imperative in critiquing our article, which is aimed at interpreting process sedimentology using core and outcrop. We have published 14 core photographs and one outcrop photograph showing various sedimentological details, but Higgs (2002) has failed to comment on details of any of those photographs. We would have found his discussion scientifically meaningful had he based his critique on his direct examination of core and outcrop used in our study or on his critique of our observations made on those photographs. In our response presented in this article, we show that Higgs's (2002) discussion is irrelevant to the central theme of our article, which is interpretation of core and outcrop in understanding tidal processes in estuarine environments. We address each major issue in the same order and heading under which Higgs (2002) discussed them.

*Department of Geology, University of Texas at Arlington, P.O. Box 19049, Arlington, Texas, 76019; shanshanmugam@aol.com.

**ExxonMobil Development Company, Kashagan Subsurface Team, 12450 Greenspoint Drive, Houston, Texas, 77060-1905; mike.poffenberger@exxonmobil.com.

Manuscript received April 23, 2001; final acceptance August 30, 2001.

ARGUMENTS FOR SHELF, NOT ESTUARINE, DEPOSITION

Lack of Emergence Indicators

According to Higgs (2002), evidence for subaerial exposure, such as marsh facies, is a must in an estuarine sequence. In part because marsh facies are uncommon in the Hollin and Napo formations, he questions the validity of our estuarine model. The problem with this simplistic view of estuaries is that modern estuaries are much more complex than idealized models (Dalrymple et al., 1992, p. 1144). Therefore, interpretation of ancient sequences as estuarine facies is quite challenging. The presence of sparse marsh facies in the cored intervals of the Hollin and Napo formations can be explained by many factors. First, we applied the tide-dominated estuary model to the Hollin and Napo formations (Shanmugam et al., 2000, figure 25, stages 2 and 3). In this model, transgressive successions are the norm in the Hollin and Napo formations (see Shanmugam et al., 2000, figure 22). As Dalrymple et al. (1992, p. 1132) state, "estuaries can only form in the presence of a relative sea-level rise (i.e., a transgression)." Therefore, marsh facies are unlikely to be present in a transgressive, deepening-upward succession (Figure 1). In contrast, a prograding, shallowing-upward succession is likely to contain marsh facies near the top (Dalrymple, 1992, figure 12). Because "the Hollin and Napo formations do not show shallowing-upward trends" (Shanmugam, et al., 2000, p. 679), marsh facies are not expected to develop. Second, we placed our study locality of the Sacha field at the outer estuary margin where marsh facies do not develop (Shanmugam et al., 2000, figure 25). Third, Dalrymple et al. (1992, p. 1142–1143) state that erosion of facies commonly produces the equivalent of a ravinement surface in tide-dominated estuaries. This contradicts Higgs's (2002) assertion that removal of all the marsh facies by ravinement surface is overly fortuitous. Fourth, our study area is small enough to fit into a large estuary (Shanmugam et al., 2000, p. 673). Higgs's (2002) argument against this possibility is that

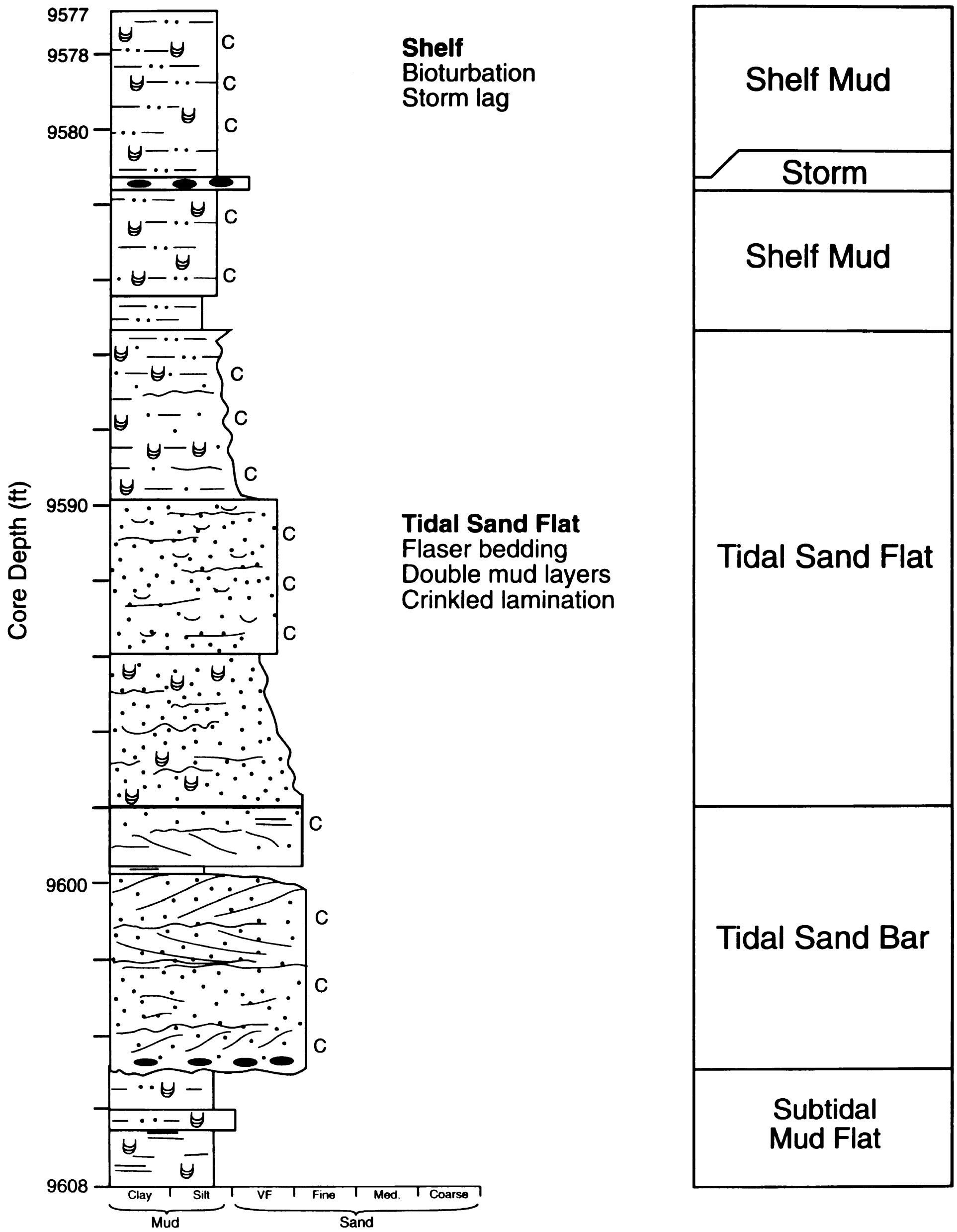

Figure 1. Sedimentological log of core from the Sacha 129 well Napo U sand showing fining/thinning-upward, transgressive succession, Sacha field, Ecuador.

"Hollin-Napo T-U facies association continues laterally for more than 100 km in all directions, with no known breaks"; however, Higgs provides no data in support of his claim. Finally, the number of cored intervals available for study is also a controlling factor.

Higgs (2002, p. 329) states that our fluvial channel interpretation "is based solely on 'cross stratification and basal lags'." In reality, we also stated (Shanmugam et al., 2000, p. 656–657), "In this study, the main difference between tidal and fluvial channels is that tidal channels exhibit cross-beds with mud drapes, whereas cross-beds in fluvial channels do not typically show mud drapes."

Higgs's (2002) frequent reference to his unpublished work in the Putumayo Basin in Colombia as a major source of data or evidence in support of his shelf model throughout his discussion is difficult to evaluate. What we need is a reliable correlation of core data from Colombia with core data from Ecuador to establish a sedimentological link between the two basins.

According to Higgs (2002), marsh environments comprise a large part of an estuary. In supporting his view, Higgs (2002) cites figure 24a in Shanmugam et al. (2000) and claims that 30–80% of an estuary is made up of marsh facies. Figure 24a in Shanmugam et al. (2000) is a conceptual diagram of a tide-dominated estuary from Dalrymple et al. (1992). Because this diagram is not drawn to scale, it is unscientific to quantify this diagram.

Higgs (2002, p. 330) claims, "Hollin-Napo T-U facies association continues laterally for more than 100 km in all directions, with no known breaks (see following sections)." Subsequently, in his discussion under the subheading Great Areal Extent, Higgs (2002) states, " The characteristic Hollin-Caballos and Napo-Villeta T-U facies association (see previous sections) extends for at least 150 km north to south (Oriente-Putumayo Basin)." Unfortunately, Higgs (2002) does not provide any new data in justifying his claim of great areal extent of facies.

Higgs (2002) claims that we wrongly used the Bristol Channel estuary as a modern analog. We used this analogy following Harris's (1988, table 1, p. 274) classification of the Bristol Channel as an estuary. Higgs (2002) argues that the Bristol Channel is not an estuary but a shelf seaway. In fact, our estuarine model is not based on the Bristol Channel analogy but on examination of rocks from the Sacha field.

Lack of Intertidal Indicators

Higgs (2002) states that we did not report diagnostic intertidal sedimentary structures, such as desiccation cracks. This is misleading because supratidal zones are characterized by rooted muds and desiccation cracks, whereas intertidal zones are characterized by flaser bedding, wavy bedding, and lenticular bedding (see Dalrymple, 1992, figure 12). We did, in fact, include core photographs of flaser bedding, wavy bedding, and lenticular bedding that characterize sand flat facies (see Shanmugam et al., 2000, figures 11, 13, 16).

Great Areal Extent

Several of Higgs's (2002) statements are misleading, and his references are selective in promoting a shelf model for the Hollin and Napo formations. For example, (1) Higgs (2002) refers to the work of Dashwood and Abbotts (1990), who proposed the great lateral extent of Hollin facies for at least 100 km in the Oriente Basin. Dashwood and Abbotts (1990, p. 94), however, interpreted the Hollin Formation as deposits of fluvial, braided stream to littoral environments, not just shelf environments. Dashwood and Abbotts's (1990) conclusion is based on isopach maps of the entire Hollin Formation. By design, these isopach maps do not distinguish braided fluvial from littoral facies. In contrast, our core study is meant to distinguish each individual depositional facies (fluvial channels, tidal channels, tidal sand bars, sandy shelves, etc.). Therefore, Higgs's (2002) use of Dashwood and Abbotts's (1990) generalized interpretations based on isopach maps is not appropriate in critiquing our precise interpretations based on core study. (2) Higgs (2002) refers to the work of Pindell and Tabbutt (1995) in justifying a broad north-south marine shelf from Bolivia to Venezuela during the Aptian–Albian. Pindell and Tabbutt's (1995, figures 4, 5) maps are paleogeographic maps that show distribution of three generalized environments, namely, continental, shallow marine, and deep marine. In these maps, shallow-marine environments apparently include both estuarine and shelf environments. Therefore, Higgs's (2002) use of these maps, which do not have the provision for distinguishing estuarine environments as a separate entity from shelf environments, as evidence against our estuarine interpretation is clearly misleading. (3) Although Higgs (2002) refers to the work of Dashwood and Abbotts (1990) in supporting his shelf model, he selectively ignores Dashwood and Abbotts's (1990, p. 94) interpretation of the Napo formation as tidal channels in an estuarine environment. (4) Finally, Higgs (2002) argues that the great marine transgression in the Aptian–Albian, expressed on a sea level curve, is the evidence against our estuarine model. The development of estuaries during transgression, however, is the norm (Dalrymple et al., 1992, p. 1132). Higgs's (2002) methods of interpreting the Hollin and Napo formations as simple blanket sands deposited on a broad shelf stretching over the entire continent of South America are inappropriate in critiquing our site-specific core study.

Lack of Evidence for Incision (Incised Valleys)

Higgs (2002) argues that estuaries occupy incised valleys by definition (Dalrymple et al., 1992) and, therefore, our estuarine model is not valid if we reject an incised-valley interpretation. This argument is skewed because there are at least four major types of estuaries: (1) drowned river valleys, (2) bar-built estuaries, (3) fjords, and (4) tectonic estuaries (Strahler and Strahler, 1974). Estuaries defined by Dalrymple et al. (1992) belong to the first category (i.e., drowned river valleys). We pointed out that the angular unconformity at the base of the Hollin is the result of tectonic uplift and erosion (Shanmugam et al., 2000, p. 674). Therefore, the Hollin-Napo estuary belongs to the fourth category (i.e., tectonic estuaries). Furthermore, Dalrymple et al. (1994, p. 3) state, "We urge that the term 'incised valley' be restricted to fluvially eroded features that are larger than a single channel." This means that the concept of "incised valley," based on sea level changes, in a sequence stratigraphic framework is applicable only to drowned river valleys and not to tectonic estuaries.

Limited Ichnofauna and Microfauna

In supporting his tidal shelf model, Higgs (2002) suggests scarcity of ichnofauna and microfauna in the Hollin and Napo formations. In interpreting depositional processes and environments, we always give primary importance to sedimentary structures and only give tertiary importance to ichnofauna and microfauna.

Environmental Summary

Higgs (2002, p. 331) claims, "A shallow-marine interpretation is already well established for the Hollin (Baldock, 1982)"; however, Baldock (1982) is an explanatory bulletin of the national geologic map of Ecuador and, therefore, cannot establish the local depositional environments in our study area. Higgs's (2002) reference to a geologic map in justifying his shelf interpretation undermines the sedimentological progress that we have made using core and outcrop data.

Higgs (2002) proposes a tidal shelf model for the Hollin and Napo formations based on modern tidal shelf deposits (Belderson et al., 1982; Stride et al., 1982). Modern shelf deposits cannot be compared with the Hollin and Napo formations because of incongruent data sets. For example, Belderson et al. (1982, p. 27) used the following data sets in studying tidal bedforms in modern environments: (1) side-scan sonar, (2) echo-sounder profiles, and (3) underwater photographs and television. An important data set missing from this list is core. In their study of modern offshore tidal deposits, Stride et al. (1982, p. 125) concluded, "The structures of the sand facies are poorly known and should be sampled as a matter of urgency." As such, these studies of modern deposits are concerned primarily with studying external morphology, not internal stratification. In fact, Stride et al. (1982) constructed a series of hypothetical cross sections and inferred internal stratification (see Stride et al., 1982, figures 5.13, 5.20, 5.21, 5.22). In contrast, we actually observed bidirectional cross-bedding, fanning of the foresets (full vortex), reactivation surfaces, double mud layers, crinkled laminae, and so on in the core of the Hollin and Napo formations. On the basis of these observations, we have established tidal bundles in the Hollin and Napo formations. These structures have hydrodynamic implications for tidal processes. To make a meaningful sedimentological analog of modern deposits for the Hollin and Napo formations, Higgs (2002) needs to document tidal bundles with full-vortex structures, double mud layers, and crinkled laminae in core from modern tidal shelf deposits.

In addition, the presence of tidal bundles in the Hollin and Napo argues against Higgs's (2002) tidal shelf interpretation because, as Johnson and Baldwin (1996, p. 260) state, "Tidal bundles and sand/mud couplets have only been positively identified in the tidal deposits of inshore areas and coastal embayments and this may enable distinction between these and offshore environments." The absence of delicate structures, such as double mud layers, in modern shelf environments may be due to destruction of delicate structures by vigorous shelf currents. In contrast, delicate structures are preserved in a protected estuarine environment.

Tidal sand ridges in shelf environments tend to show a characteristic coarsening/thickening-upward facies succession (Mutti et al., 1985). In contrast, the Napo U sand shows a fining/thinning-upward trend (Figure 1). Based on these scientific grounds, we totally reject Higgs's (2002) proposal of an alternative tidal shelf model for the Hollin and Napo formations in the Sacha field.

IMPLICATIONS FOR RESERVOIR SAND GEOMETRY

General

We believe that Higgs (2002) has failed to establish a viable depositional model based on examination of core and outcrop and that any discussion of the significance of his model in petroleum exploration and development is not reliable.

Sand-Body Geometry

In support of his distinction between estuary and shelf (i.e., offshore), Higgs (2002) cites an article by Belderson (1986, p. 293), who states, "In the context of this paper, 'offshore' will also apply to the outer estuary and embayment." This means that the distinction between outer estuary and shelf is not that great. In the Sacha 129 well, a sedimentological log of the Napo U sand shows the vertical transition from estuarine facies with tidal sand bars to shelf facies with storm deposits (Figure 1). This vertical facies association suggests a close spatial relationship between the mouth of the estuary and the shelf. We have also published identical facies relationships in the Sacha 132 well (see Shanmugam et al., 2000, figure 22). For these reasons, we have placed our study locality of the Sacha field at the outer estuary in stages 2 and 3 (Shanmugam et al., 2000, figure 25). Most of Higgs's (2002) discussion is a reflection of his lack of understanding of this important sedimentological aspect of our depositional model.

Sand-Body Orientation

We have already rejected Higgs's (2002) model on scientific grounds, and, therefore, this discussion on sand-body orientation based on his model is not relevant.

SEQUENCE STRATIGRAPHY

We are puzzled by Higgs's (2002) lengthy discussion on sequence stratigraphy because our study (Shanmugam et al., 2000) is a sedimentological one based on actual core and outcrop data. We need to respond to the following items, however, because they are misleading.

1. In discussing the A and B limestones, Higgs (2002, p. 331) states, "these so-called limestone units are actually interbedded shale and argillaceous limestone, the latter comprising concretionary bands and nodules, formed of calcite-cemented shelly siliciclastic mud." We would like to know in what well and at what cored intervals Higgs has made these observations. We do not understand how he arrived at this observation because none of the wells that we studied (see Shanmugam et al., 2000, figure 26) has cored intervals from the A and B limestones.
2. In further discussing the A and B limestones, Higgs (2002, p. 331) states, " . . . but are locally capable of producing oil from fractures." Considering that these limestones are not cored in our study area, we wonder in what wells he studied the presence of fractures.
3. Higgs (2002) suggests an incised-valley exploration play with fluvial and/or estuarine facies in the Hollin and Napo formations in the Sacha field based on his examination of correlation panels in the Coca-Payamino and Gacela fields. First of all, fluvial and/or estuarine facies are in direct conflict with his proposed shelf model. Second, the Coca-Payamino and Gacela fields are outside our study area of the Sacha field. Third, our estuarine interpretation is based on examining rocks, not correlation panels. Clearly, Higgs (2002) has missed the main theme of our article, which is the study of core and outcrop in interpreting depositional processes and environments.
4. Higgs (2002) uses sharp bases of the T and U sands in our figures 23 and 26 (Shanmugam et al., 2000) as evidence for a shelf model. The T and U sands, however, are not cored through their basal contacts in our studied wells (see Shanmugam et al., 2000, figures 23, 26). Apparently, Higgs (2002) uses wire-line log motifs in establishing facies contacts. To make a meaningful sedimentological interpretation of facies contacts, one must examine actual basal contacts of sand beds in core and outcrop. Otherwise, the very sedimentologic value of establishing the nature of facies contacts by examining rocks is lost.

In summary, our method of interpreting specific depositional processes and environments based on core and outcrop is essential in establishing this complex tide-dominated estuarine depositional system. Higgs's (2002) methods of interpreting generalized environments, based on paleogeographic maps, isopach maps, correlation panels, wire-line log motifs, and sea level curves are insufficient for making these process sedimentologic interpretations.

REFERENCES CITED

Baldock, J. W., 1982, Geology of Ecuador (explanatory bulletin of the national geological map of the Republic of Ecuador): Ministerio de Recursos Naturales y Energéticos, Dirección General de Geología y Minas, Quito, Ecuador, 59 p.

Belderson, R. H., 1986, Offshore tidal and non-tidal sand ridges and sheets: differences in morphology and hydrodynamic setting, *in* R. J. Knight and J. R. McLean, eds., Shelf sands and sandstones: Canadian Society of Petroleum Geologists Memoir 11, p. 293–301.

Belderson, R. H., M. A. Johnson, and N. H. Kenyon, 1982, Bedforms, *in* A. H. Stride, ed., Offshore tidal sands: London, Chapman and Hall, p. 27–57.

Dalrymple, R. W., 1992, Tidal depositional systems, *in* R. G. Walker and N. P. James, eds., Facies models: response to sea level change: Geological Association of Canada, p. 195–218.

Dalrymple, R. W., B. A. Zaitlin, and R. Boyd, 1992, Estuarine facies models: conceptual basis and stratigraphic implications: Journal of Sedimentary Petrology, v. 62, p. 1130–1146.

Dalrymple, R. W., R. Boyd, and B. A. Zaitlin, 1994, History of research, types and internal organization of incised-valley systems: introduction to the volume, *in* R. W. Dalrymple, R. Boyd, and B. A. Zaitlin, eds., Incised-valley systems: origin and sedimentary sequences: SEPM Special Publication 51, p. 3–10.

Dashwood, M. F., and I. L. Abbotts, 1990, Aspects of the petroleum geology of the Oriente Basin, Ecuador, *in* J. Brooks, ed., Classic petroleum provinces: Geological Society Special Publication 50, p. 89–117.

Harris, P., 1988, Large-scale bedforms as indicators of mutually evasive sand transport and the sequential infilling of wide-mouthed estuaries: Sedimentology, v. 57, p. 273–298.

Higgs, R., 2002, Tide-dominated estuarine facies in the Hollin and Napo ("T" and "U") formations (Cretaceous), Sacha field, Oriente Basin, Ecuador: discussion: AAPG Bulletin, v. 86, no. 2, p. 329–334.

Johnson, H. D., and C. T. Baldwin, 1996, Shallow clastic seas, *in* H. G. Reading, ed., Sedimentary environments: processes, facies and stratigraphy, 3d ed.: Oxford, England, Blackwell Science, p. 232–280.

Mutti, E., J. Rossell, G. Allen, F. Fonnesu, and M. Sgavetti, 1985, The Eocene Baronia tide dominated delta-shelf system in the Ager Basin, *in* D. Mila and J. Rossell, eds., Excursion guidebook: 6th International Association of Sedimentologists European Regional Meeting, p. 577–600.

Pindell, J. L., and K. D. Tabbutt, 1995, Mesozoic–Cenozoic Andean paleogeography and regional controls on hydrocarbon systems, *in* A. J. Tankard, R. Suárez, and H. J. Welsnik, eds., Petroleum basin of South America: AAPG Memoir 62, p. 101–128.

Shanmugam, G., M. Poffenberger, and J. Toro Alava, 2000, Tide-dominated estuarine facies in the Hollin and Napo ("T" and "U") Formations (Cretaceous), Sacha field, Oriente Basin, Ecuador: AAPG Bulletin, v. 84, p. 652–682.

Strahler, A. N. and A. H. Strahler, 1974, Introduction to environmental science: Santa Barbara, California, Hamilton Publishing, 633 p.

Stride, A. H., R. H. Belderson, N. H. Kenyon, and M. A. Johnson, 1982, Offshore tidal deposits: sand sheet and sand bank facies, *in* A. H. Stride, ed., Offshore tidal sands: London, Chapman and Hall, p. 95–125.