Late Paleozoic to Cenozoic history of the offshore Sydney Basin, Atlantic Canada

Vincenzo Pascucci, Martin R. Gibling, and Mark A. Williamson

Abstract: The Sydney Basin covers a large offshore area south of Newfoundland, with a well-exposed outcrop belt on Cape Breton Island. The geological history of the poorly known offshore area is interpreted using an industry seismic grid and Lithoprobe line 86-5, tied to outcrops and two wells. The mid-Devonian to Upper Carboniferous – Permian basin fill is 6–7 km thick and represents three extensional phases with intervening and succeeding compressive phases. The mid-Devonian McAdams Lake Formation was deposited in a local half-graben during early post-Acadian extension. Following deformation, a suite of Early Carboniferous extensional basins filled mainly with Horton Group conglomerates developed on northeast-trending and southeast-dipping master faults. Some faults developed along Acadian terrane boundaries. The Windsor Group extends over the master faults to onlap basement as a result of thermal sag and Visean eustatic rise. Mid-Carboniferous deformation, linked to the Alleghanian orogeny, reactivated faults and caused basin inversion and a basinwide unconformity. Upper Carboniferous to ?Permian coal measures and redbeds were subsequently deposited in a broad basin that developed over the Early Carboniferous basins. Subsidence may reflect extension on major faults in the Cabot Strait coupled with thermal sag and (or) continued sag on an underlying mid-crustal detachment. After coalification, Acadian terrane boundaries and other lineaments were reactivated during a compressive tectonic episode, probably during the Permian. The basin's polycyclic history, with repeated subsidence and inversion phases, has important implications for hydrocarbon systems.

Résumé : Le bassin Sydney recouvre une grande zone extracôtière au sud de Terre-Neuve et présente une ceinture d'affleurements bien exposés sur l'île du Cap-Breton. L'histoire géologique de la région, peu connue au large, est interprétée au moyen d'une grille sismique industrielle et la ligne Lithoprobe 86-5 et elle est rattachée à des affleurements et à deux puits. Le matériau de remplissage du bassin, Dévonien moyen à Carbonifère supérieur – Permien, a une épaisseur de 6 à 7 km et il représente trois phases d'extension et des phases de compression intermédiaires successives. La Formation de McAdams Lake, Dévonien moyen, a été déposée dans un demi-graben local au cours d'une extension post-acadienne précoce. Après déformation, des bassins d'extension formant une suite datant du Carbonifère précoce se sont remplis surtout de conglomérats du Groupe de Horton; ces derniers se sont développés sur de grandes failles à direction nord-est et à pendage sud-est. Quelques failles se sont développées le long des limites du terrane acadien. Le Groupe de Windsor s'étend sur les failles principales jusqu'à recouvrir le socle suivant l'affaissement thermal et le relèvement eustatique viséen. La déformation au Carbonifère moyen, liée à l'orogène alléghanien, a réactivé des failles et causé une inversion de bassin et une discordance à travers tout le bassin. Les gîtes houillers et les gisements de type red-beds du Carbonifère supérieur au ?Permien ont ensuite été déposés dans un vaste bassin qui s'est développé au-dessus des bassins du Carbonifère précoce. De la subsidence peut refléter une extension sur les failles majeures dans le détroit de Cabot jumelée à un affaissement thermique et (ou) un affaissement continu sur un détachement sous-jacent mi-crustal. Après la formation de la houille, les limites du terrane acadien et d'autres linéaments ont été réactivés au cours d'un épisode de compression tectonique, probablement au cours du Permien. L'historique polycyclique du bassin, avec ses phases répétées de subsidence et d'inversion, a des implications importantes pour les systèmes hydrocarbonés.

[Traduit par la Rédaction]

Introduction

The Sydney Basin forms part of the regional Maritimes Basin of Atlantic Canada, the upper Paleozoic fill of which covers the southern Gulf of St. Lawrence and parts of the Grand Banks of Newfoundland. Strata of the Sydney Basin are exposed onshore in Cape Breton Island and extend offshore to Newfoundland and eastward under the Burin Platform (Fig. 1); the eastern boundary of the basin has not been defined. Northward, the basin is bordered by fault zones of the Cabot Strait, associated with small depocentres that include Upper Paleozoic strata (Langdon and Hall 1994). These faults separate the Sydney Basin from the central part of the Maritimes Basin beneath the Gulf of St. Lawrence. Southward the basin is bordered by Proterozoic rocks of Scatarie Ridge (Fig. 1).

The Sydney Basin has been a major coal-mining area since the 1700s and has potential for hydrocarbons. Coal has been mined onshore and offshore (within about 10 km of the coastline) since the early 1700s. Hydrocarbons are present in

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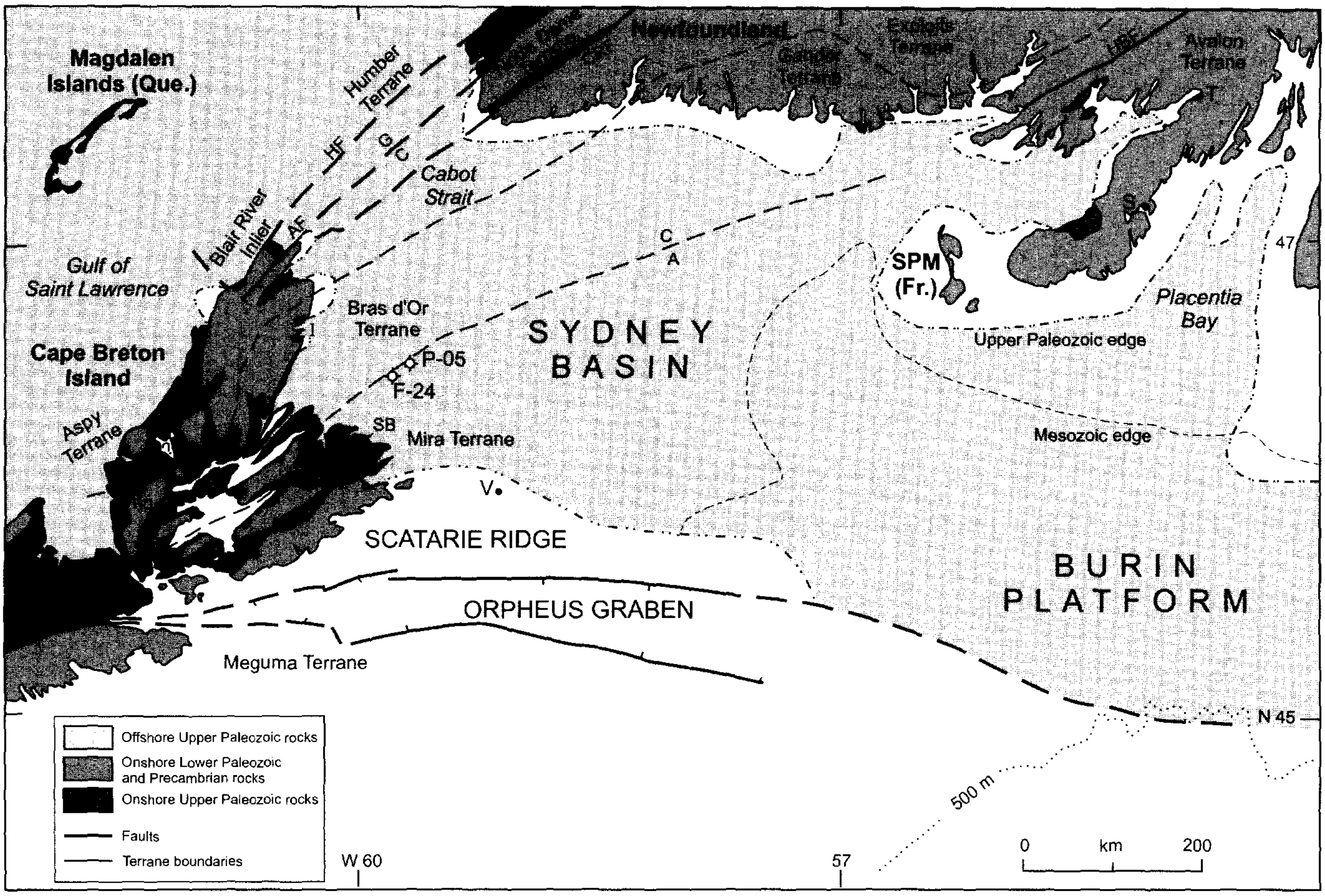
Fig. 1. Geological setting of the Sydney Basin in Atlantic Canada. Onshore extent of upper Paleozoic rocks from Keppie and Muecke (1979) and Colman-Sadd et al. (1990), and the approximate offshore extent of upper Paleozoic and Mesozoic rocks from Bell and Howie (1990). Terrane boundaries from Barr et al. (1995, 1998), and location of Scatarie Ridge and Orpheus Graben from Jansa et al. (1993). Approximate boundaries of lower-crustal blocks in offshore area from Marillier et al. (1989): A, C, and G denote the Avalon, Central, and Grenville lower-crustal blocks, respectively. Other locations mentioned in the text are as follows: I, Ingonish; RD, River Denys; S and T, outcrops at Terrenceville and Spanish Room Point, respectively, on the Burin Peninsula; SB, onshore and nearshore strata of the Sydney Basin; V, volcanic rocks on Scatarie Ridge (Jansa et al. 1993). Major faults are as follows: AF, Aspy; CCF, Cobequid–Chedabucto; CRF, Cape Ray; HBF, Hermitage Bay; HF, Hollow; LRF, Long Range. F-24 and P-05 indicate positions of offshore wells. SPM (Fr.), St. Pierre and Miquelon (France).



sandstones and along faults in the mines (Haites 1951), and gas emerges at the sea floor along faults (Courtney 1996). Oil shows are evident in the basal carbonates of the Windsor Group. Farther offshore, the Murphy et al. North Sydney P-05 and Shell et al. North Sydney F-24 wells (Fig. 1) recorded numerous gas shows. General geological and geophysical assessments for the offshore area were made by Sheridan and Drake (1968) and King and MacLean (1976), who described the basinal fill as 4–5 km thick and saucer-shaped, with beds dipping towards a deeper central area under the Atlantic Ocean. However, the stratigraphic and tectonic framework of the offshore area has received little attention.

The present study brings together well and seismic information to interpret the upper Paleozoic and Mesozoic history of the offshore Sydney Basin. The study updates an earlier synthesis by Gibling et al. (1987) based mainly on the onshore area. A large suite of poor-quality industry seismic lines is available, and 14 lines of higher quality and Lithoprobe deep-crustal seismic line 86-5 (Fig. 2) were selected to illustrate the upper Paleozoic section of the basin. Apart from mines and coal drill holes in the nearshore zone near Sydney, direct lithological information about the offshore strata is limited to data from the F-24 and P-05 wells (Fig. 2), which penetrated up to 1700 m of strata. This information is supplemented by the excellent onshore exposures near Sydney (SB, Fig. 1), which were crucial in interpreting the seismic profiles. The principal geological aspects of these exposures (Fig. 3) which relate to the offshore stratigraphic setting are illustrated in Fig. 4 and described in the next section.

Geological setting of the Sydney Basin and adjacent areas

Basement rocks

Precambrian and lower Paleozoic rocks on Cape Breton Island have been assigned to several terranes (Fig. 1) that amalgamated prior to or during the mid-Devonian Acadian orogeny (Barr et al. 1995, 1998). Probable correlation of terrane boundaries to southern Newfoundland is shown in

Fig. 2. Location map to show seismic coverage for the offshore Sydney Basin, modified from Geological Survey of Canada database. Designated areas represent different seismic quality: A, good quality; B, poor quality (severe multiples); C, poor quality but with less severe multiples. Although all lines were examined, the bold lines show seismic profiles from which most interpretation was drawn. Six industry lines and the Lithoprobe line are illustrated here (Figs. 8–14), lines 81-1119 and 81-1121 were illustrated by Langdon and Hall (1994), and lines 81-1102, D-94, D-98, D-102, and D-106 show many multiples but provide some information about the eastern offshore area.

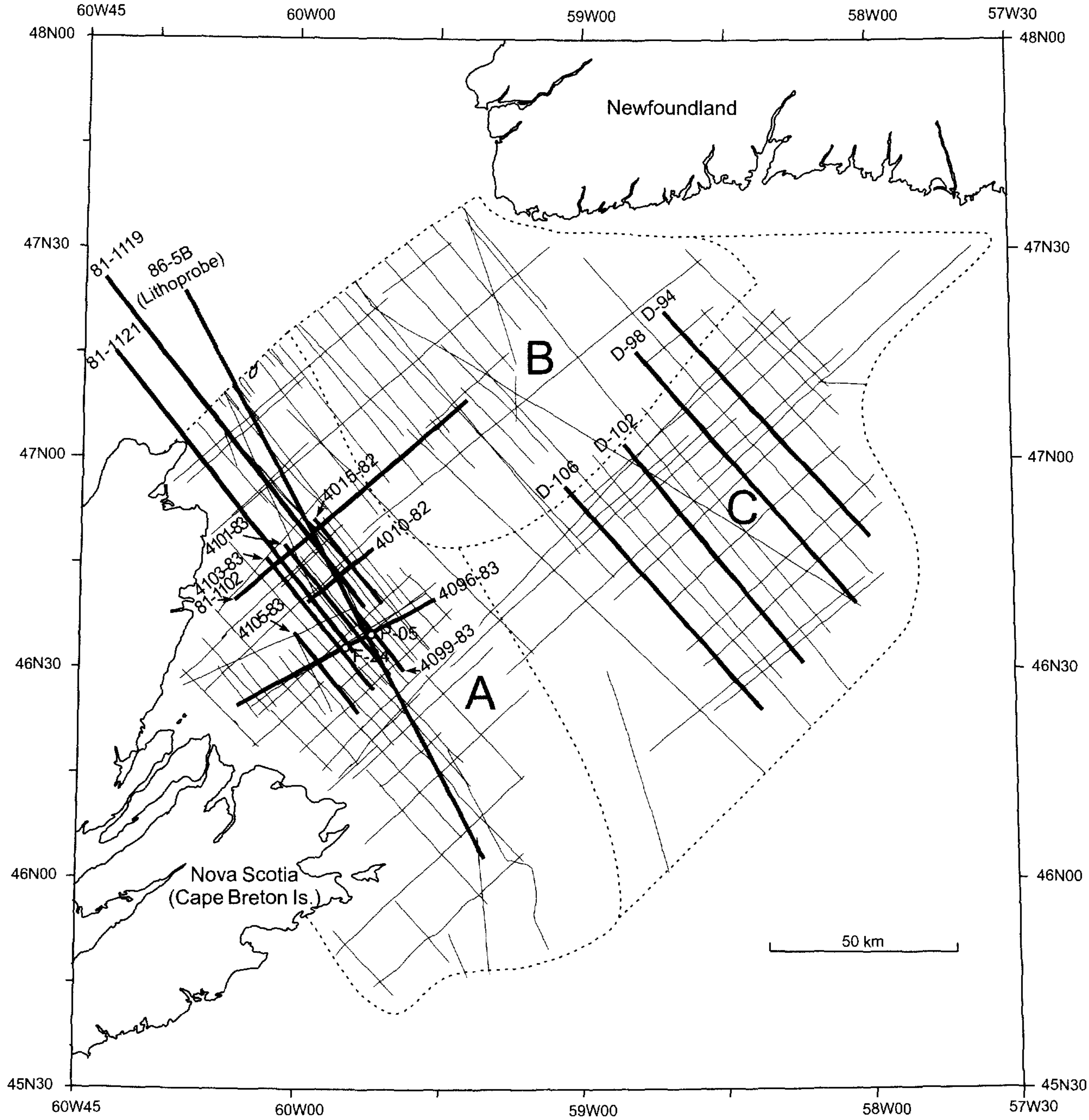


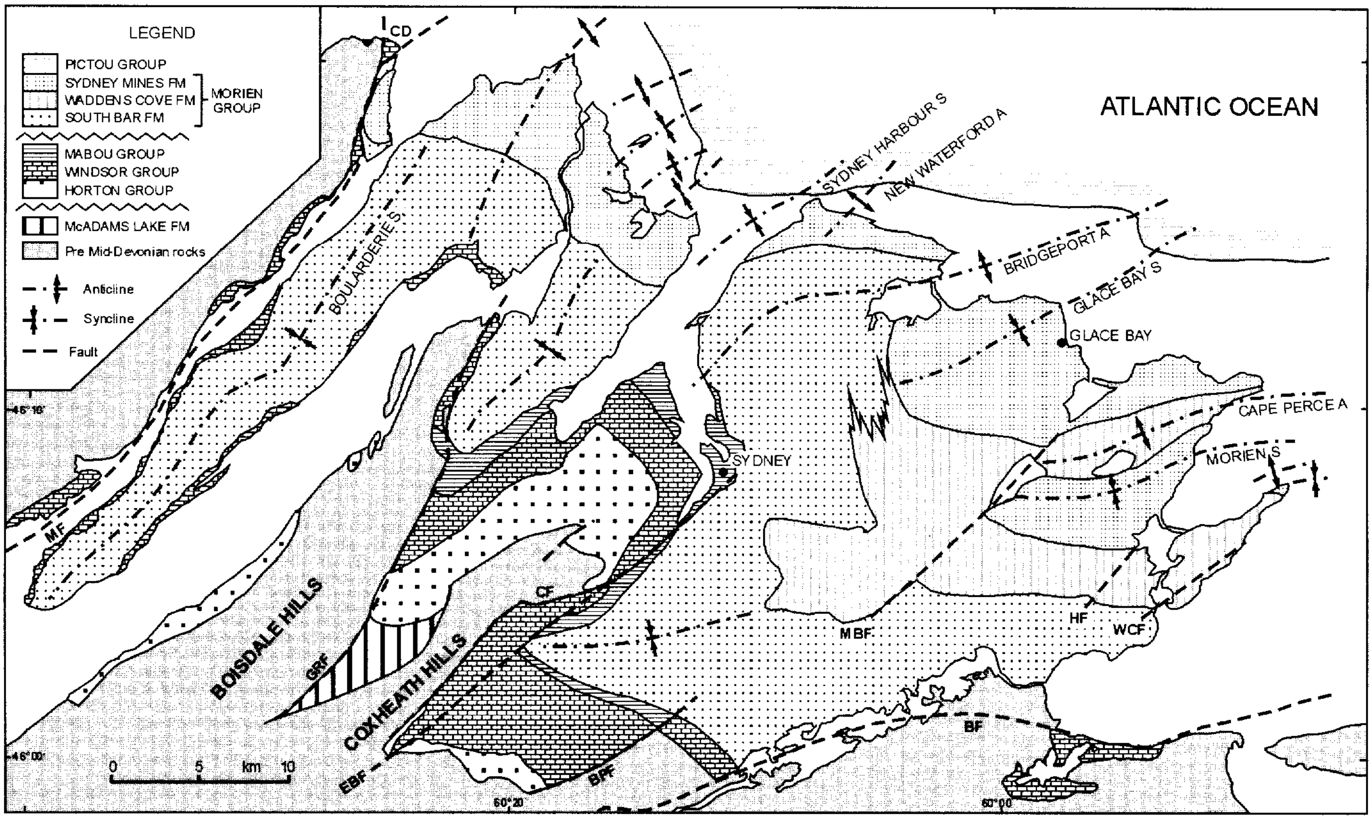
Fig. 1. Two boundaries correspond with lower-crustal discontinuities identified in Lithoprobe line 86-5, between the Avalon, Central, and Grenville blocks (Marillier et al. 1989) (Fig. 1). As discussed later in the paper, some terrane boundaries appear to be reactivated and probably formed persistent lines of weakness.

Quinlan (1988) suggested that the upper Paleozoic depocentre of the Gulf of St. Lawrence originated by extension on southeast-dipping surfaces at lower crustal levels (Marillier et al. 1989), which he interpreted as thrusts formed during earlier tectonic episodes. An inferred detachment under the Sydney Basin (Marillier et al. 1989) may have originated in a similar manner, as an Acadian thrust front lies in western Newfoundland north of the Sydney Basin (Stockmal et al. 1998).

Devonian and Carboniferous rocks

The mid-Devonian McAdams Lake Formation (Fig. 3) comprises coarse siliciclastic strata, organic-rich shale and coal, of lacustrine and alluvial origin. The strata were laid

Fig. 3. Geological map of the onshore Sydney Basin. Major faults are as follows: BF, Bateston; BPF, Big Pond; CF, Coxheath; EBF, East Bay; GRF, Georges River; HF, Homeville; MBF, MacAskills Brook; MF, Mountain; WCF, Waddens Cove. A, anticline; CD, Cape Dauphin locality; S, syncline. Modified from Boehner and Giles (1986) and White and Barr (1998).



down in a half-graben during postorogenic extension along the Mira – Bras d'Or terrane boundary (White and Barr 1998) and subsequently deformed.

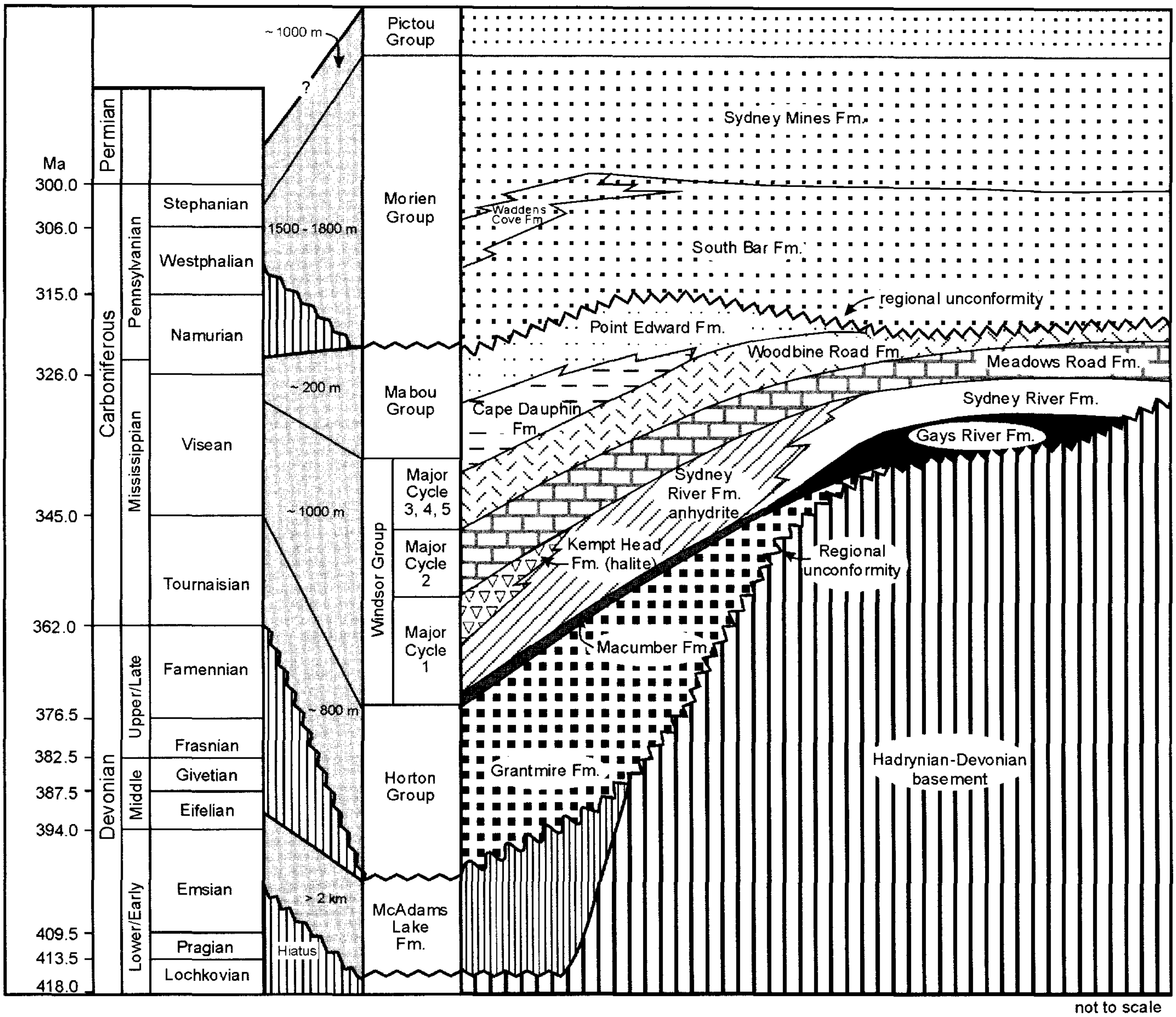
The Tournaisian Grantmire Formation of the Horton Group rests on an angular unconformity (Figs. 4, 5*a*). It consists mainly of alluvial-fan and braided-stream conglomerates and is up to 800 m thick, wedging out locally (Giles 1983). Although the Grantmire Formation has not received detailed tectonic analysis, the Horton Group occupies fault-bounded basins across Atlantic Canada (Hamblin and Rust 1989), and similar basins with probable Horton fill were imaged on Lithoprobe line 86-5 (Marillier et al. 1989). Volcanic rocks of the Fisset Brook Formation underlie the Horton Group in western Cape Breton, and organic-rich shales are prominent at mid-levels of the Horton Group regionally: neither have been proven in the Sydney Basin.

The Visean Windsor Group is up to 1000 m thick but is highly variable in thickness (Boehner 1986). It overlies the Grantmire Formation with apparent concordance and oversteps it locally to rest on basement rocks (Figs. 4, 5*b*). Basal units comprise carbonate buildups of the Gays River Formation and dark laminated limestone of the Macumber Formation (Fig. 4). Basal carbonates at Cape Dauphin (Fig. 3) and nearby Fairy Hole contain granitic boulders, testifying to strong relief during early Windsor deposition. The overlying strata comprise siliciclastics, carbonates, sulphate evaporites, halite, and minor potash salts. The local Kempt Head Formation contains a thick halite section (up to 327 m), although evaporites may not be prominent elsewhere in the basin (Giles 1983). The overlying lacustrine Mabou Group consists of sandstone, siltstone, shale, limestone, and sulphate evaporites, with some thick dark shales.

The Morien Group (late Westphalian B to Stephanian) is up to 1800 m thick and rests unconformably on the Mabou and Windsor groups (Fig. 4). The basal South Bar Formation consists mainly of braided-fluvial sandstones with minor coal, at least 860 m thick (Rust and Gibling 1990). The overlying Sydney Mines Formation is ~1000 m thick and consists of sandstone, mudstone, economic coals, dark limestone, and calcrete, deposited in alluvial to restricted marine conditions (Gibling and Bird 1994; Tandon and Gibling 1997). The Waddens Cove Formation is a local alluvial-redbed equivalent of these two formations. Red mudstone and sandstone of the Pictou Group (Stephanian to ?Permian) underlie the nearshore area and may be 1000 m thick based on dip extrapolation (R.C. Boehner, personal communication, 1999).

Northeast-trending faults cut the Devonian and Lower Carboniferous strata, but most faults cannot be traced across the basal Morien unconformity (Fig. 3), which implies that tectonic activity was mid-Carboniferous or older. Both Lower and Upper Carboniferous strata dip gently, typically at 5–20°, and the Morien Group exhibits broad northeast- to east-trending folds (Fig. 3). Stratal thickness (Robb 1876; Hacquebard 1983) and facies evidence (Gibling and Bird 1994; Tandon and Gibling 1997; Tibert and Gibling 1999) indicate that some synclines were paleotopographic lows during Morien deposition, suggesting modest Late Carbonif-

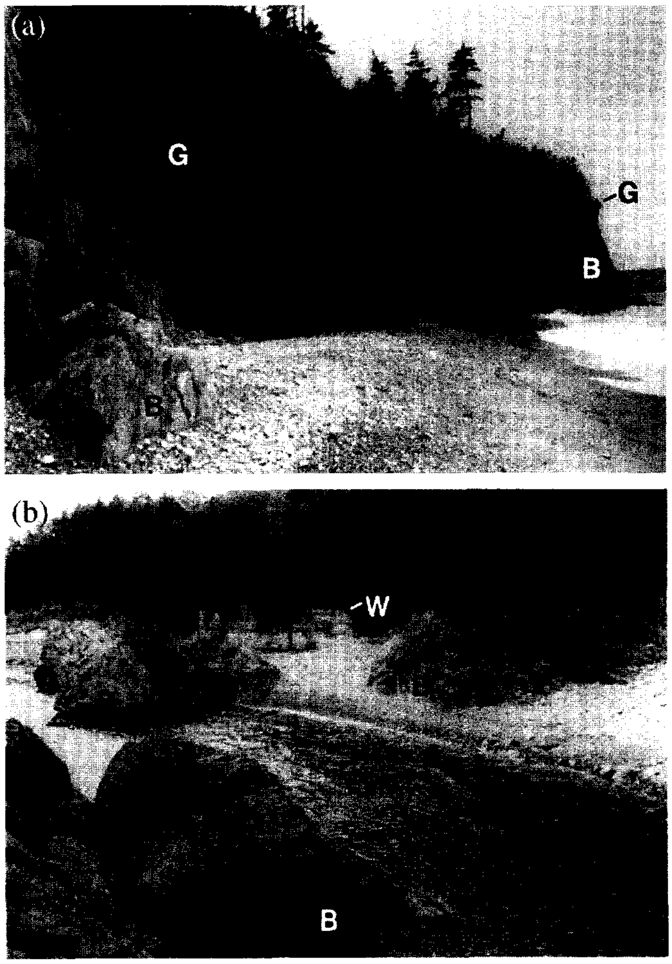
Fig. 4. Stratigraphic relationships and age for rock units onshore in the Sydney Basin. Modified from Boehner and Giles (1986) and unpublished data from R.C. Boehner. Time scale for base of Visean and above from Okulitch (1995), which uses the estimates of Hess and Lippolt (1986), with lower boundaries from Tucker et al. (1998).



erous fault movement and (or) compactional draping over the faulted blocks (Hacquebard 1983). The basin-bounding Mountain and Bateston faults cut the Morien Group, which may be overthrust along the Bateston Fault (R.C. Boehner, personal communication, 1999). Morien strata dip steeply near the Georges River Fault and at up to 50° on the limbs of the Bridgeport and Cape Perce anticlines (Fig. 3), where they are cut by low-angle reverse faults with northwest strikes and throws up to tens of metres (Haites 1951, 1952; Hacquebard 1983; Courtney 1996). Few faults are sufficiently large to be resolved using industry seismic lines. Haites (1951) suggested a latest Carboniferous to Permian age for the deformation by comparison with the United States Appalachians and Europe.

Horton, Windsor, and Mabou strata crop out along the eastern Cape Breton Highlands, where a Horton half-graben has been documented (Hamblin and Rust 1989). Near Ingonish (Fig. 1), the Windsor Group rests on basement rocks (Fig. 5*b*) and includes carbonate mounds (van der Gaag et al. 1996). Carboniferous strata, including Windsor diapirs, occupy fault-bounded basins in the Cabot Strait (Langdon and Hall 1994). Tournaisian (Horton equivalent) alluvial and lacustrine rocks, including dark shales, are present on the Burin Peninsula (S and T, Fig. 1), where they are overlain unconformably by alluvial (Mabou Group?) strata (Laracy and Hiscott 1982; Hyde 1995). Coal-bearing Westphalian B–D strata overlie basement rocks in Placentia Bay (King et al. 1986; Miller 1987), and Lower and Upper Carboniferous strata, including Windsor diapirs, underlie the Burin Platform and the eastern Grand Banks (Bell and Howie 1990; MacLean and Wade 1992; Pascucci et al. 1999), possibly within a distinct depocentre.

Fig. 5. Carboniferous outcrops of the Sydney Basin and adjacent areas. (*a*) Alluvial conglomerates of the Grantmire Formation (G), Cape Dauphin (CD in Fig. 3). They rest with nonconformity upon basement rocks (B) that include the Kellys Mountain Pluton (dated at 498 Ma by Barr et al. 1990) and are cut by faults. The conglomerates form a thin layer that progressively oversteps basement rocks to the west (in distance) and is overstepped in turn by the Windsor Group. Person at centre right for scale. (*b*) Flat-lying evaporitic rocks of the Windsor Group (W) in nonconformable relationship with basement rocks (B) at Keltic Lodge, Ingonish (I in Fig. 1). Windsor outcrops are ~3 m high.



Permian–Cenozoic rocks

Post-Carboniferous strata are poorly known in the Sydney Basin, but are present elsewhere in the region. Lower Permian rocks underlie the Gulf of St. Lawrence (van de Poll et al. 1995), and Permian intrusions and thermal events have been documented in southwestern Nova Scotia and Prince Edward Island (Zentilli and Reynolds 1985; Dallmeyer and Keppie 1987; Pe-Piper and Loncarevic 1989; Greenough and Fryer 1991). Permian deformation, magmatism, and metamorphism are prominent in the United States Appalachians (Dallmeyer 1982; Wintsch and Sutter 1986; West and Lux 1993), where dextral shear probably reflects convergence of Gondwana and Laurentia at 270–290 Ma (Getty and Gromet 1988; Sacks and Secor 1990; Goldstein 1994; Valentino et al. 1994). Faure et al. (1996) inferred a Permian tectonic phase in Quebec and northern New Brunswick from structural evidence.

The Orpheus Graben (Fig. 1) contains a thick Late Triassic to Cenozoic succession. Cretaceous rocks overlie the upper Paleozoic section on the Burin Platform (MacLean and Wade 1992), the eastern Sydney Basin (Fig. 1), and at River Denys in Cape Breton Island (RD, Fig. 1) (Dickie 1987), and Lower Cretaceous igneous rocks were dredged from the Scatarie Ridge (V, Fig. 1) (Jansa et al. 1993). Tectonic activity and erosion associated with the Avalon Uplift affected the Grand Banks from the Late Jurassic to the Late Cretaceous (Grant and McAlpine 1990), and some upper Paleozoic faults were reactivated during the Mesozoic (e.g., Plint and van de Poll 1984; MacLean and Wade 1992). Mesozoic basin inversion and reverse faulting in the Fundy area were provisionally dated as Early Jurassic or later by Withjack et al. (1995). Fission-track analysis indicates that the Maritimes Basin underwent prolonged exhumation that commenced by the Middle or Upper Triassic, resulting in erosion of several kilometres of latest Paleozoic to early Mesozoic strata (Hendriks et al. 1993; Grist et al. 1995).

Offshore wells

The P-05 well (Murphy Oil Company 1974; Barss et al. 1979) and F-24 well (Shell Canada Resources Limited 1976; Dolby and LaBorde 1976) were drilled on a basement high and provide stratigraphic ties to some seismic lines used in the study. The P-05 well (Fig. 6) penetrated a Westphalian B–C to Stephanian section of red Pictou Group strata underlain by 740 m of the coal-bearing Morien Group. The low thickness of Morien strata is in accord with the well location on a basement high (Hacquebard 1983). A prominent unconformity, identified in the biostratigraphic analysis, separates the Morien Group from 170 m of underlying red to grey shale, siltstone, sandstone, and limestone, dated as late Visean to early Namurian and assigned to the Mabou Group. The thickness of these strata is comparable with that of the Mabou Group onshore. The basal, undated 120 m of conglomerate with minor carbonate probably belongs to the Windsor Group: the apparent absence of the Macumber or Gays River facies suggests that the conglomerate overlies these units, consistent with a Windsor attribution. The F-24 well shows a similar succession (Fig. 6), although the basal strata are sandstones rather than conglomerates.

Seismic database and depth conversion

Industry seismic lines in the public domain (Fig. 2) were obtained using variable air gun arrays and streamer lengths by Petro-Canada, Murphy Oil, and Texaco between 1970 and 1982. Seismic quality is variable (Fig. 2), but a suite of lines with fair resolution was obtained by Petro-Canada offshore northeastern Cape Breton Island. These lines are tied to the F-24 and P-05 wells. Most of our analysis centres in this region, and six lines document our interpretations (Figs. 8–13, with a general model in Fig. 7). Elsewhere in the basin, strong multiples make interpretation problematic for low-quality lines, which were used only to trace prominent structural features and groups of reflectors. Lithoprobe line 86-5 crosses the basin (Fig. 2). Acquisition parameters

Fig. 6. Lithological columns and sonic logs for the F-24 and P-05 wells (Fig. 1). Modified from Geological Survey of Canada well database. Hacquebard (1976) appraised coals from P-05 cutting samples and sonic logs (not all coals were identified on lithological logs), and his correlations with coals onshore have been used in delineating formations within the Morien Group. The estimated dip in this well is about 20°, and thicknesses are apparent and overestimated

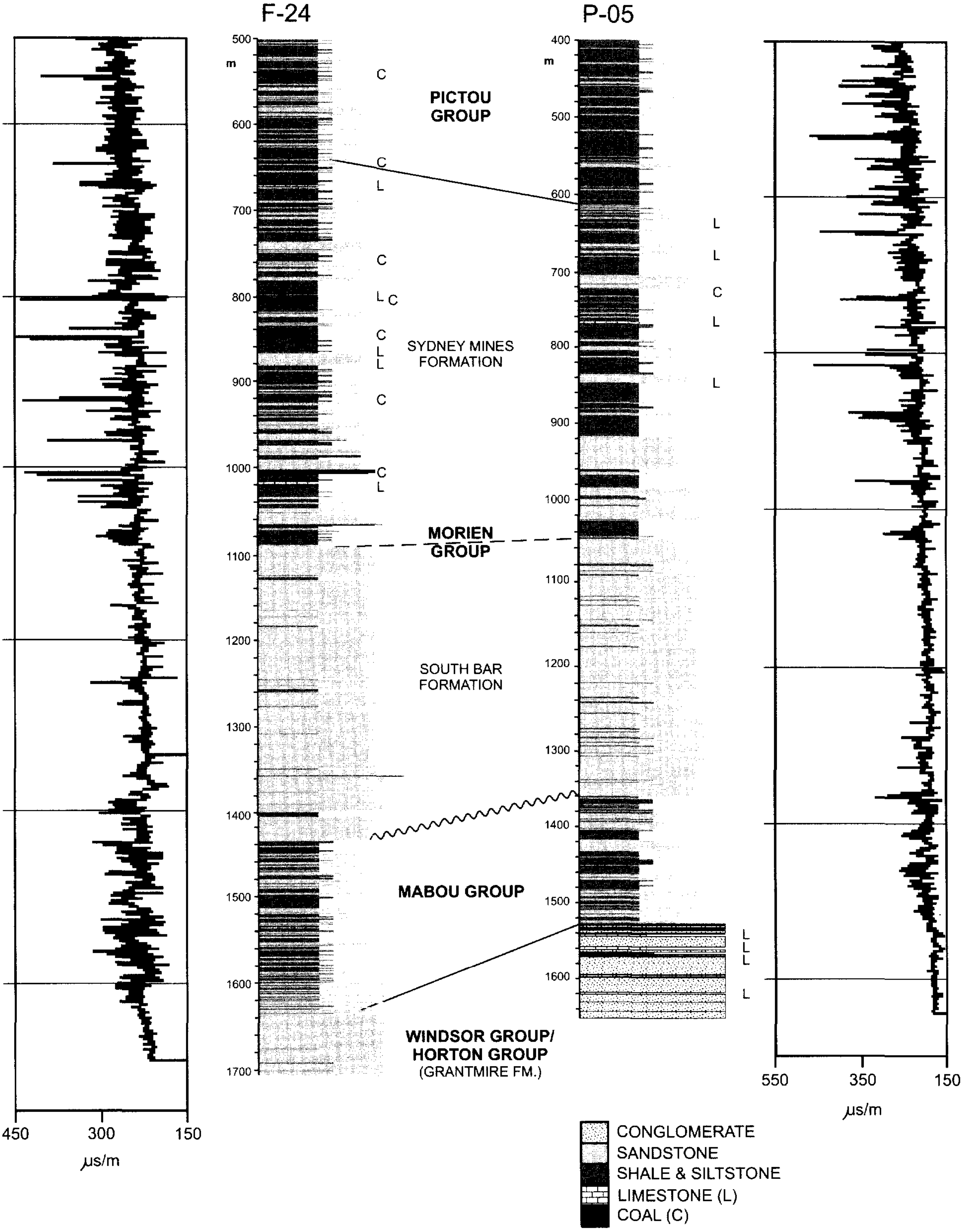


Fig. 7. Schematic representation of a generalized seismic line to show key surfaces (A–C) and upper Paleozoic rock units (1–3) recognized in seismic lines in the Sydney Basin study area. Thick black lines are faults.

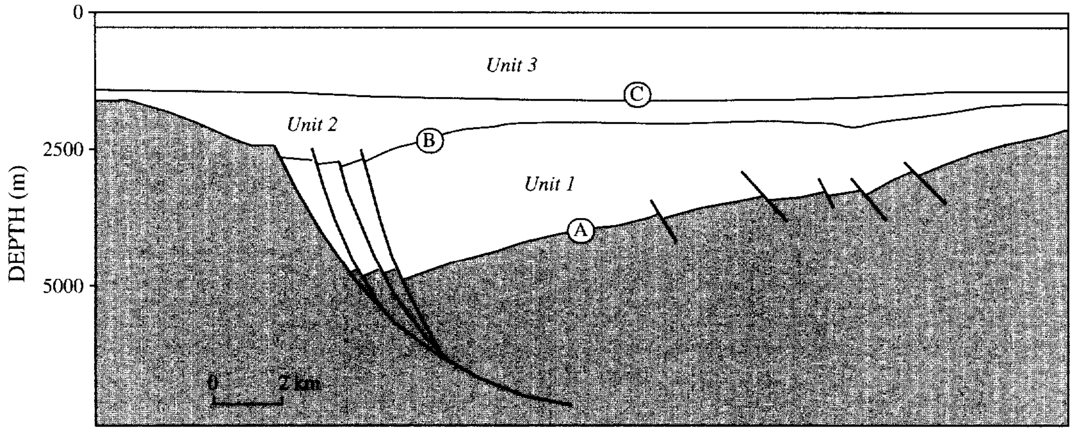
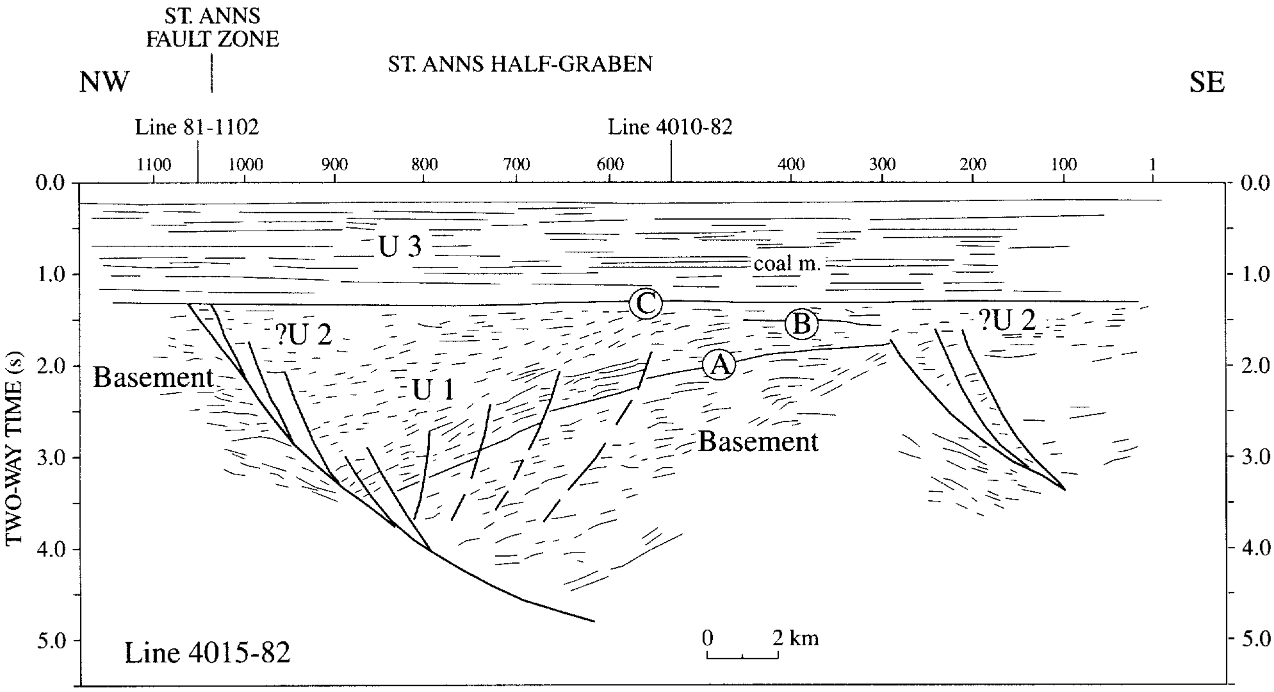


Fig. 8. Line 4015-82. See Fig. 6 for location. A, B, and C, bounding surfaces; U1, U2, and U3, seismic units; coal m, prominent zone of reflectors attributed to the Morien Group coal measures. Names of half-grabens and fault zones apply to events associated with units 1 and 2.

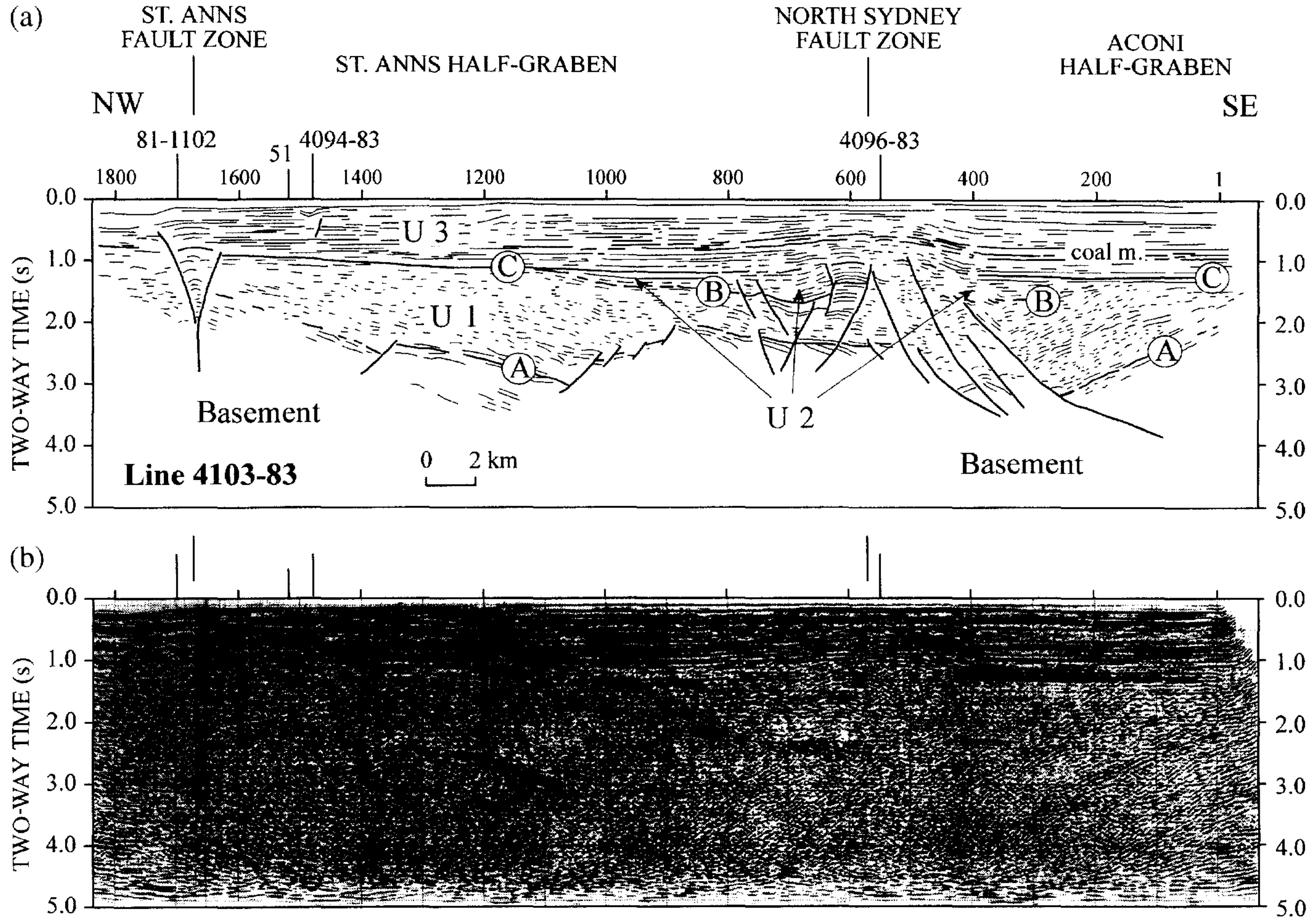


were designed to enhance resolution at mid- to deep-crustal levels (Marillier et al. 1989), and sea-floor multiples mask parts of the upper Paleozoic section. However, useful information was obtained from a copy that had been reprocessed and migrated to enhance shallow reflectors. An interpreted section (Fig. 14) was checked against the better quality industry lines and was especially valuable in the southern basin area where industry lines provide little information. The Lithoprobe line and five industry lines cross the prevailing northeast–southwest structural grain of the basement rocks, evident from onshore maps (Fig. 3) and aeromagnetic maps offshore (Loncarevic et al. 1989). One line (4096-93) runs subparallel to the structural grain and close to the wells (Fig. 2). Lines 81-1119 and 81-1121 run from the Sydney Basin across the Cabot Strait and were illustrated by Langdon and Hall (1994).

To estimate stratigraphic thickness from two-way traveltime (TWT), we use 2950 m/s for seismic unit 3 (Pictou and Morien groups), 3800 m/s for unit 2 (Mabou and Windsor groups), and two values of 4000 and 5000 m/s to provide a range of estimates for unit 1 (Horton Group). These estimates, justified below, allow approximate depth conversion for reflectors near the P-05 well. However, limited velocity information and the low quality of most lines preclude the construction of accurate depth maps.

Reflectors on line 4096-83 were tied to horizons in the P-05 well for which a seismic velocity survey and time–depth curve are available (Shell Canada Limited 1974). An average

Fig. 9. Line 4103-83, interpreted (*a*) and uninterpreted (*b*). See Fig. 6 for location. Abbreviations as in Fig. 8.



velocity of 2950 m/s was estimated from the surface to the base of the well, an interval that comprises mainly Morien and Pictou strata. The base of the inferred Morien coal-reflector package lies at 0.65 s TWT, which corresponds to 961 m depth, close to the 1040 m estimated for the well (Fig. 6). The inferred basal Morien unconformity lies at 1.1 s TWT, which corresponds to 1490 m depth, close to the 1360 m depth estimated in the well. For deeper strata, stack velocities for the Lithoprobe line near P-05 are about 3800 m/s at an inferred basal Windsor level, and 5250 m/s at 2.7 s TWT at the base of a half-graben inferred to contain Horton strata. Using these estimates, the upper Paleozoic strata may be 7 km thick. Hall et al. (1992) used a velocity of 4 km/s for Horton–Windsor strata in Newfoundland, and MacLean and Wade (1993) used 4.4 km/s for Windsor evaporites and 4 km/s for siliciclastic Carboniferous rocks in the Burin Platform. Using these estimates would yield a maximum upper Paleozoic thickness of ~5500 m for the Sydney Basin.

Seismic units

Three distinctive surfaces (A–C) separate three seismic megasequences (units 1–3) within the basin fill (Fig. 7). The underlying basement rocks show poorly organized reflectors, although some coherent reflectors are observed locally (Figs. 8, 10, 12). These rocks are probably equivalent to the mid-Devonian and older rocks that underlie the Horton Group onshore in Cape Breton Island.

Unit 1

Surface A separates unit 1 from basement rocks. The basal reflectors dip at about 30° variously to east and west and in places show strong divergence from reflectors below surface A (Figs. 9, 12). Onlap relations were not identified with certainty. Where no divergence is visible, the base of unit 1 is recognized by a pronounced change in seismic facies (Figs. 8, 11, 13). The maximum thickness of unit 1 is 1.5 s TWT (3.0–3.75 km), and three seismic facies were identified. The basal facies has well-marked (high-amplitude), parallel reflectors that form a quasi-continuous package visible in all the illustrated lines. The second facies characterizes the bulk of the unit and has short, discontinuous, poorly marked (low-amplitude) reflectors that are generally subparallel. Locally, however, the reflectors are disorganized and chaotic (Fig. 9, shotpoints 400–600 and 1600–1800; Fig. 11, shotpoints 400–600), in areas interpreted as fault zones. The third facies is a localized but recurrent feature of the middle part of unit 1 and has short, closely spaced and well-marked parallel reflectors (Fig. 9, shotpoints 100–300; Fig. 10, shotpoints 1500–1700; Fig. 11, shotpoints 100–300).

Unit 1 is correlated with the Horton Group, and the predominant seismic facies probably represents coarse clastic

Fig. 10. Line 4096-83, interpreted (*a*) and uninterpreted (*b*). See Fig. 6 for location. Abbreviations as in Fig. 8.

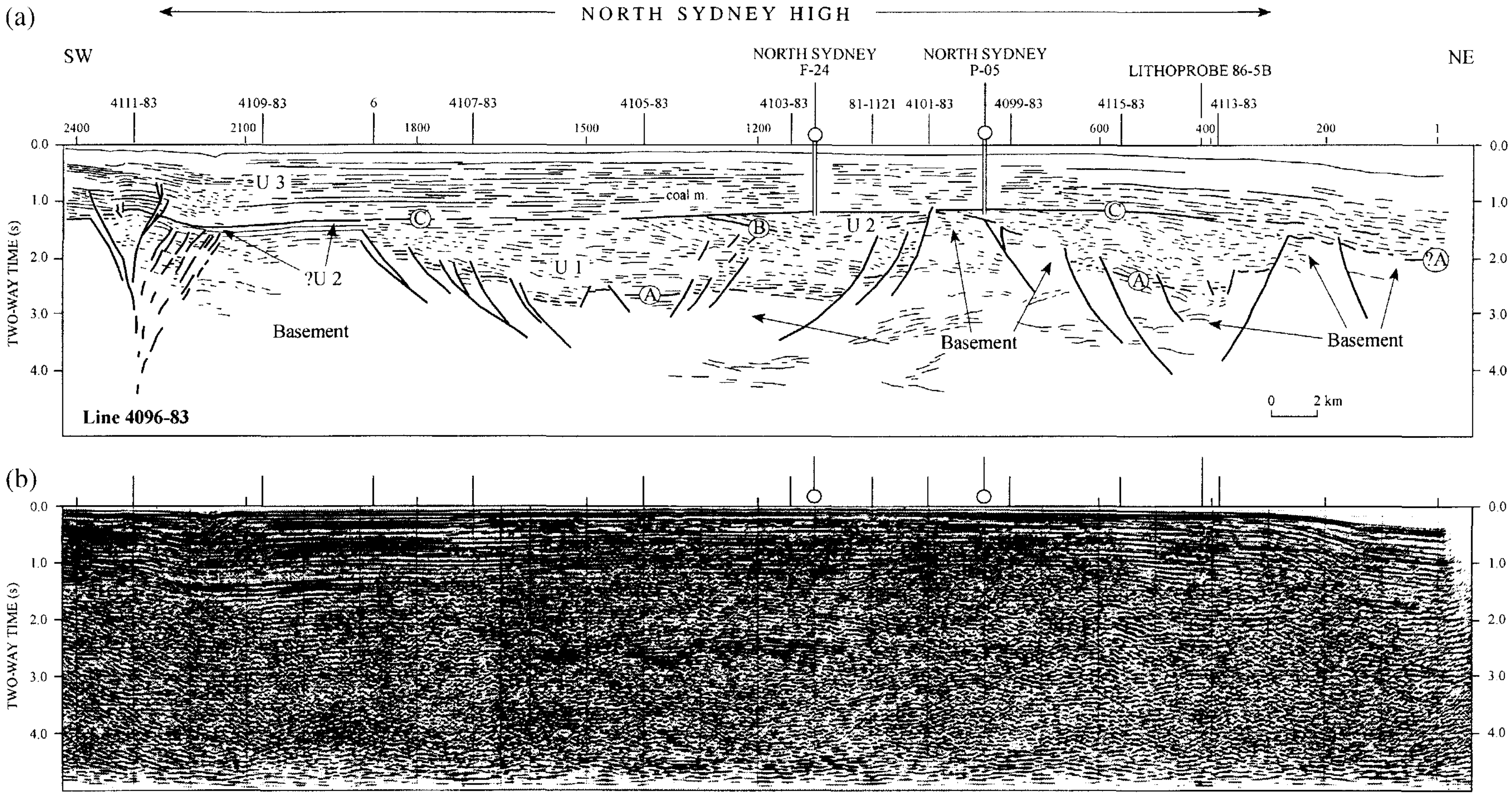
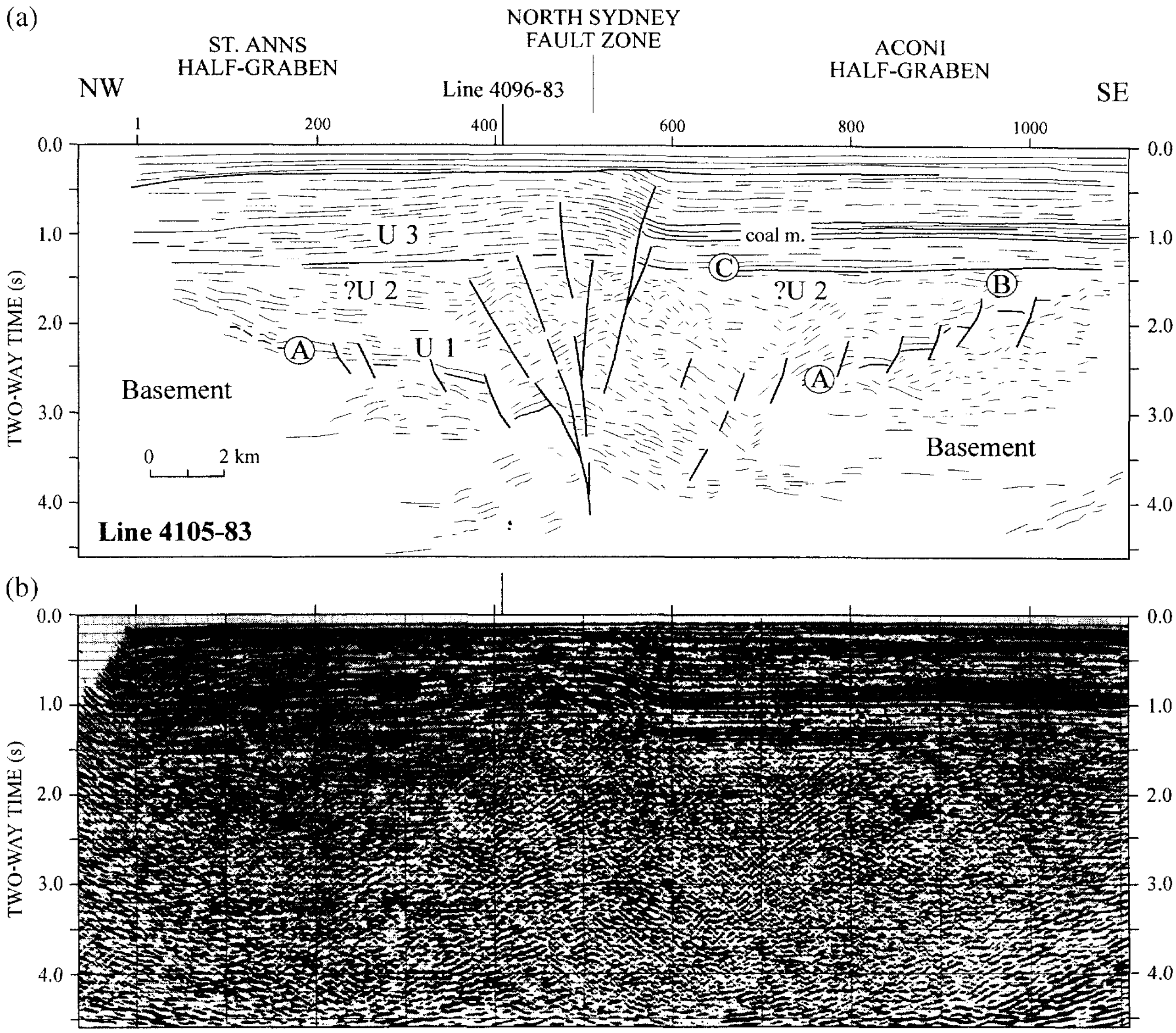


Fig. 11. Line 4105-83, interpreted (*a*) and uninterpreted (*b*). See Fig. 6 for location. Abbreviations as in Fig. 8.



strata, which predominate onshore. The basal reflector package could represent well-stratified volcanic and sedimentary strata equivalent to the Fisset Brook Formation. The local reflector package at mid levels may represent a shale-rich interval that is widely present in the region, but could also reflect volcanics or other rock types that cause acoustic impedance.

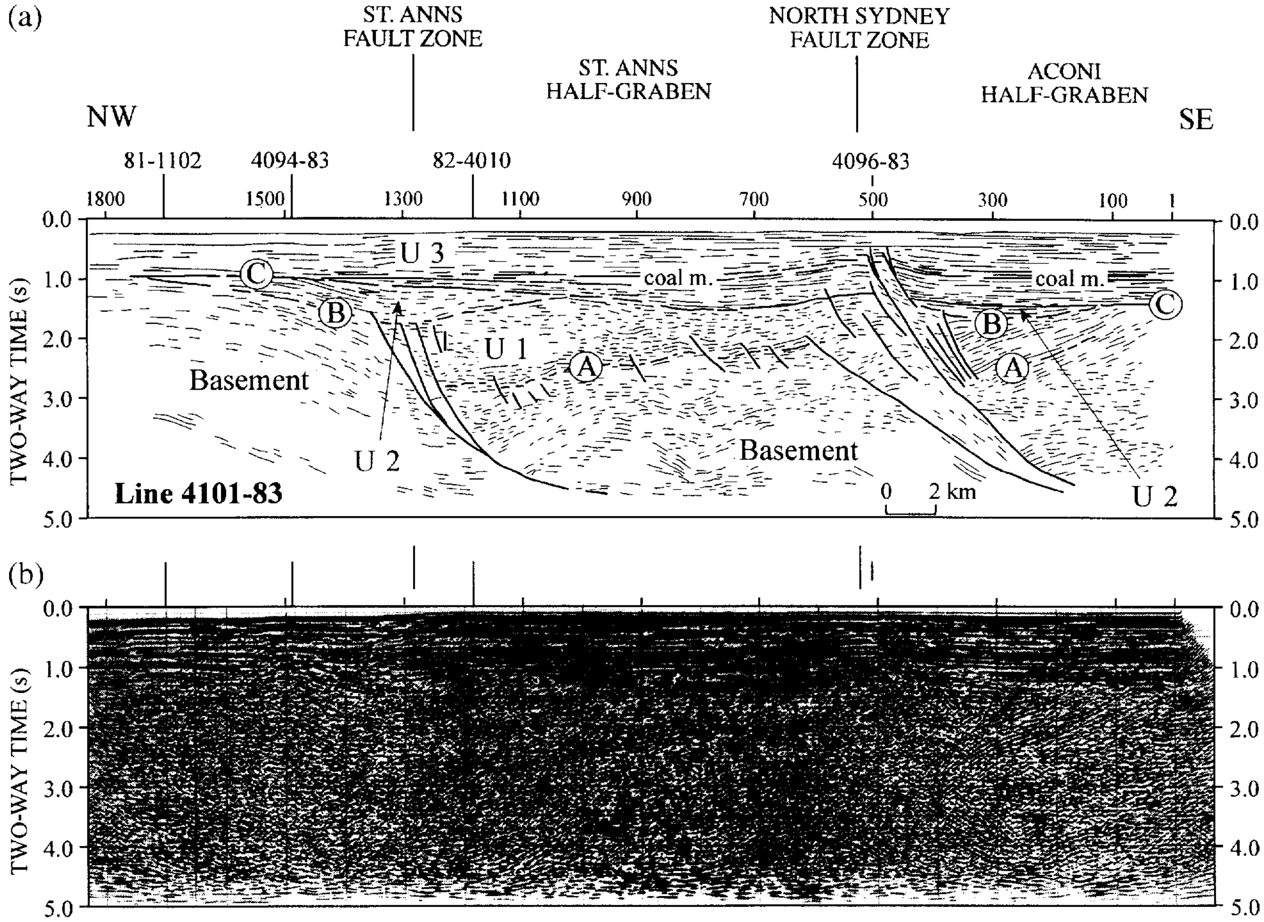
White and Barr (1998) noted that the unconformity between the McAdams Lake Formation and the Horton Group might prove distinctive in seismic lines. However, poor resolution precludes identification of the McAdams Lake Formation, which may form part of the "basement" if present offshore. The shales and coals of the formation should cause acoustic contrast, and a McAdams Lake contribution to the basal reflector package cannot be ruled out. Additionally, reflectors are present within the basement rocks.

Unit 2

Surface B marks the base of unit 2. Reflectors of unit 2 appear generally concordant with surface B but onlap the surface in places (Fig. 9, shotpoints 200–400; Fig. 12, shotpoints 1400–1600; Fig. 13, shotpoints 300–400). Surface B is inferred to be an unconformity locally. Unit 2 reflectors are mainly well marked and concave-up to planar (Fig. 10, shotpoints 2100–2000; Fig. 12, shotpoints 1100–1600). In places, they overstep the underlying strata to rest on basement rocks (Fig. 12). The maximum thickness of unit 2 is 0.6 s TWT (~1150 m), and two seismic facies are identified. The lower facies has well-marked, continuous, near-parallel reflectors. The upper facies has short, discontinuous, and generally parallel reflectors that are subparallel to those of the underlying facies. Reflectors of both facies are truncated below surface C.

We correlate the lower facies with the Windsor Group and the overlying facies with the Mabou Group (see Grant 1994 and Pascucci et al. 1999 for similar interpretations elsewhere in the region). The basal Macumber Formation of the Windsor Group (Fig. 4) may be represented by the lowermost reflector of unit 2, which might also indicate thin evaporite layers. An unconformity at the base of the Windsor Group

Fig. 12. Line 4101-83, interpreted (*a*) and uninterpreted (*b*). See Fig. 6 for location. Abbreviations as in Fig. 8.



has not previously been noted in the Sydney Basin, but is observed locally elsewhere in the Maritimes Basin (Durling and Marillier 1993; Langdon and Hall 1994).

The distinctive overstep of unit 2 onto basement rocks accords with the lower Windsor onlap near Sydney and elsewhere in the Maritimes Basin (Fig. 5B). In places, topmost Horton Group strata could contribute to the basal part of unit 2, as at Cape Dauphin where thin conglomerates underlie the Windsor Group where it oversteps onto basement (Fig. 5A). Durling and Marillier (1993) noted that Horton strata overstep extensional basin margins under the Gulf of St. Lawrence. Late Namurian to early Westphalian strata are known elsewhere in Cape Breton Island and southern Newfoundland (Boehner and Prime 1993; Hall et al. 1992), but have not been proven in the Sydney Basin: their contribution to the upper part of unit 2 cannot be ruled out. The basal conglomerates and sandstones in the wells are probably part of the Windsor Group: the wells were drilled on a basement high where coarse facies might be associated with Windsor onlap, as at Cape Dauphin and Fairy Hole.

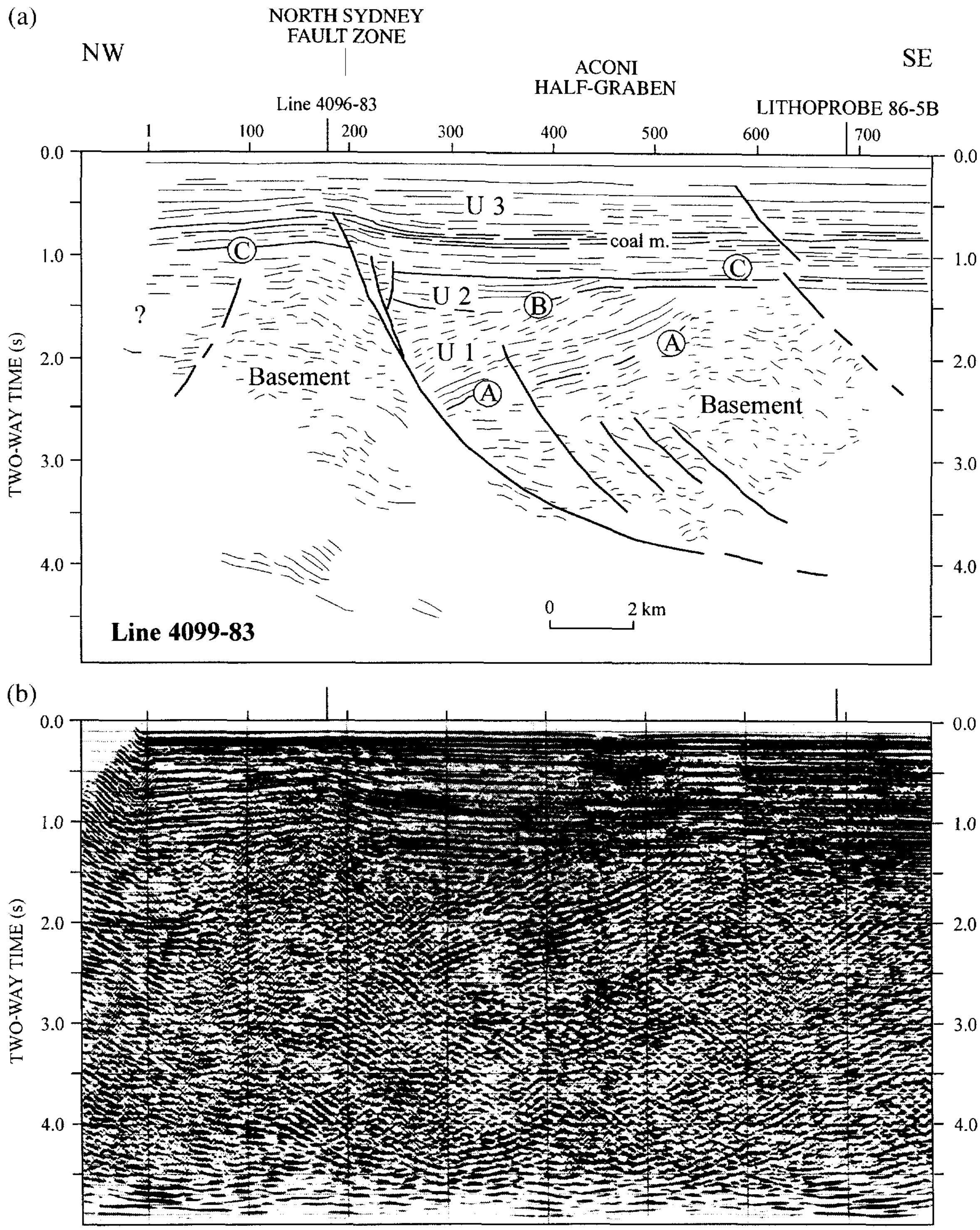
Unit 3

Surface C marks the base of unit 3, which appears to rest on basement rocks locally (Fig. 12, shotpoints 1700–1800; Fig. 13, shotpoints 100–200). It truncates all the underlying units, commonly with an angular discordance (Figs. 10, 12, 13). Reflectors of unit 3 are near-horizontal to gently dipping throughout the study area. The maximum thickness of unit 3 is 1.2 s TWT (~1800 m), and two seismic facies are recognized. The first facies characterizes the basal and topmost parts, and has discontinuous to locally continuous, parallel reflectors. The basal reflectors are near-parallel to surface C, and onlap onto this surface was identified only in the Lithoprobe line where reflectors onlap Scatarie Ridge (Fig. 14, shotpoints 100–600). The second facies characterizes the middle part of unit 3, and is recognized in all the studied lines by well-marked, continuous, closely spaced and parallel reflectors. Individual reflectors persist for short distances, but the overall aspect of the facies is maintained along the lines.

Unit 3 is assigned to the Pictou and Morien groups. The well-marked seismic facies at mid-levels is correlated with the coal-bearing Sydney Mines Formation (see Grant 1994 for a similar interpretation). The less prominent seismic facies is ascribed to the South Bar Formation where it underlies the strongly reflective facies and to the Pictou Group where it overlies the facies: coals are uncommon in both sets of strata (Fig. 6). Surface C is correlated with the prominent mid-Carboniferous unconformity seen onshore.

The top of unit 3 is bounded by an unconformity (not labelled in the figures) that cannot be recognized in all lines and is commonly masked by multiples. No well data are available to identify the unconformity, but it probably reflects the contact between the Pictou Group and Quaternary

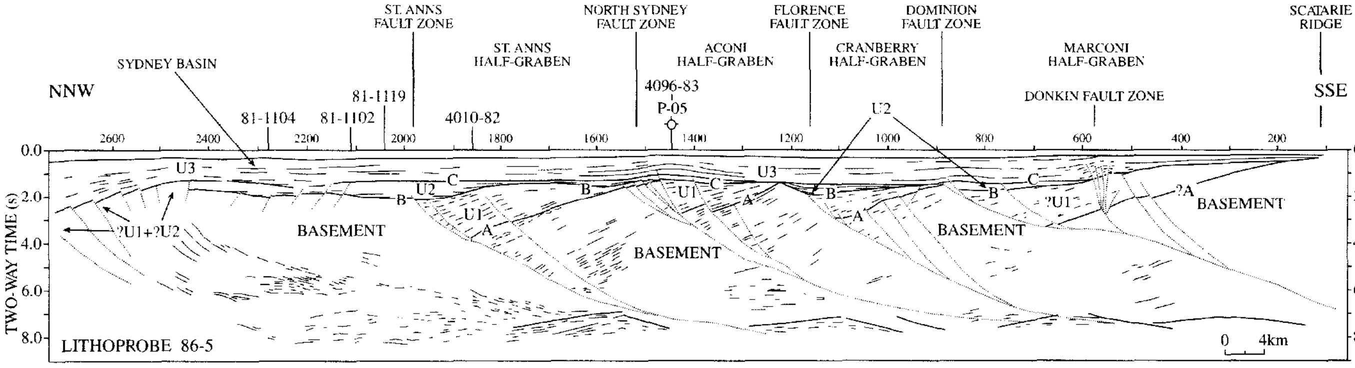
Fig. 13. Line 4099-83, interpreted (*a*) and uninterpreted (*b*). See Fig. 6 for location. Abbreviations as in Fig. 8.



deposits, as documented in the Sydney nearshore area (Courtney 1996). Langdon and Hall (1994) recognized a top Westphalian to lower Stephanian unconformity (their Barachois Unconformity) in the Cabot Strait and suggested that it correlates with the boundary between the Morien Group and overlying redbeds (Pictou Group) in the Sydney Basin. They noted that the surface becomes indistinct southward, and may be reduced to a diastem. They also identified a post-Pennsylvanian or post-Early Permian unconformity, especially near major fault zones. We were not able to confirm the presence of these surfaces in the studied lines.

In the following sections, we document development of the Sydney Basin in the context of Appalachian tectonic history. For each basinal stage, we document the geometry of the seismic units and associated structural features, followed by a broader discussion.

Fig. 14. Lithoprobe deep-crustal seismic line 86-5. See Figs. 6 and 15 for location. Uninterpreted line and an interpretation that emphasizes the deep-crustal structure are shown by Marillier et al. (1989). Ties with industry seismic lines are shown. Predominant strata in seismic units are as follows (see text): U1, Horton Group; U2, Windsor and Mabou groups; U3, Morien and Pictou groups. A, B, and C, bounding surfaces.



Early Carboniferous extensional basins

Seismic features and local depocentres

Unit 1 occupies roughly triangular areas that are well imaged on the Lithoprobe line (Fig. 14). Reflectors dip mainly northwestward but locally southeastward (e.g., Fig. 9), and their inclination commonly decreases upwards. On their downdip sides, these triangular areas are bounded by poorly imaged dislocations that are interpreted as one or more normal faults (master faults) oriented northeast–southwest and dipping mainly southeast. Synthetic and antithetic faults are associated with the master faults (Figs. 8, 9, 12, 13). The basement has varied elevation with respect to the upper Paleozoic succession and has been involved in tectonic events. The 3.0–3.75 km thickness estimated for unit 1 is in accord with up to 3 km thickness estimated for the Horton Group in Cape Breton Island (Hamblin and Rust 1989). Marillier et al. (1989) inferred from the Lithoprobe line that half-graben bounding faults were linked to a southward-dipping, mid-crustal detachment.

Unit 2 reflectors normally occupy synformal areas that, when correlated through the seismic grid, correspond to linear depressions oriented northeast–southwest. In line 4101-83 (Fig. 12, shotpoints 1000–1800), reflectors decrease in dip to near horizontal at synformal margins where they form a "wing" that onlaps unit 1 and oversteps onto basement rocks. Some small faults appear to offset unit 2, suggesting that bounding fault systems remained active locally.

The master faults can be traced northeastward from the Cape Breton coast for at least 100 km, beyond which seismic quality deteriorates. Offshore to onshore correlation of faults requires some extrapolation, and the continuity of structures could not be determined in all cases. The offshore fault zones are given formal names (Fig. 15) that differ from those of known faults onshore to allow some leeway for correlation. Interpretation of the Lithoprobe line (Fig. 14) shows four major half-grabens in the southern basinal area, all bounded by master fault zones with southward dips. The half-grabens are given formal names, derived from onshore localities, that apply only to the Early Carboniferous section, although the Morien Group may be thicker over underlying depocentres. With the exception of an area north of the St. Anns Fault Zone, basement highs between the fault-bounded basins appear narrow. Regional aeromagnetic maps (Loncarevic et al. 1989; Jansa et al. 1993) show linear zones with positive magnetic anomalies that may be interpreted as basement highs between the basins. The presence of Horton strata on the Burin Peninsula (Fig. 1) suggests that similar depocentres underlie much of the offshore area. We identify the following half-grabens, from south to north (Figs. 14, 15):

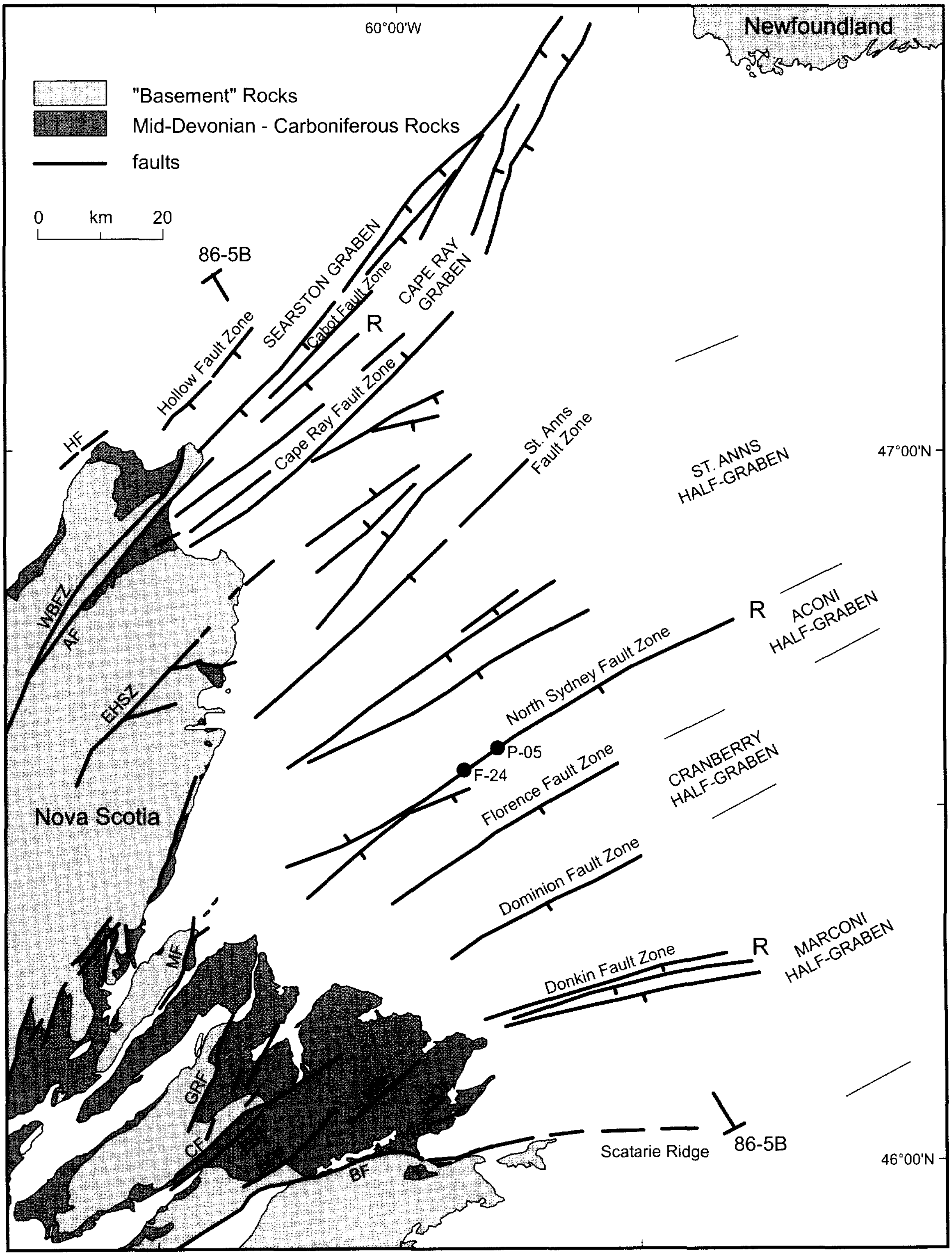
(1) The Marconi Half-graben lies at the southern end of the Lithoprobe line and is about 35 km wide. It is bordered to the north by the Dominion Fault Zone, which appears to come onshore near the Bridgeport Anticline. A distinctive aeromagnetic high links these onshore and offshore areas. The fault zone may correlate either with the Coxheath Fault or the East Bay Fault (CF and EBF, Figs. 3, 15), which border the Coxheath Hills. The half-graben strata onlap Scatarie Ridge to the south (Fig. 14). The Donkin Fault Zone is imaged within the half-graben on the Lithoprobe line, but could not be clearly resolved with industry lines.

(2) The Cranberry Half-graben is about 13 km wide and was identified on the original Lithoprobe interpretation by Marillier et al. (1989). It is bounded to the north by the Florence Fault Zone, which may correlate with a branch of the Coxheath Fault (Fig. 15). Unit 2 is prominent in the half-graben fill and oversteps onto basement rocks north of the fault zone.

(3) The Aconi Half-graben is about 13 km wide. It is bounded to the north by the North Sydney Fault Zone. The fault zone may be an extension of the Georges River Fault onshore, at the southern margin of the Boisdale Hills, and this correlation is supported by a positive aeromagnetic anomaly. No geophysical data allow us to trace this fault zone onshore into Newfoundland, but its trend suggests correlation with the Hermitage Bay – Dover fault system (Fig. 1). The prominent North Sydney High north of the fault zone, site of the North Sydney wells, was termed the Boisdale Anticline by Hacquebard (1983). The Mountain Fault may form part of the North Sydney Fault Zone, but aeromagnetic maps suggest that a magnetic high north of the fault extends offshore in a more northerly direction.

(4) The St. Anns Half-graben is about 30 km wide. It is bounded to the north by the St. Anns Fault Zone, which probably correlates with a prominent unnamed fault, mapped

Fig. 15. Major faults identified in the offshore and onshore parts of the Sydney Basin, with dip directions (where known). Most are associated with extensional basins filled mainly with strata of unit 1 and are not expressed in the overlying Morien and Pictou groups (unit 3). Fault positions offshore are derived from analysis of a seismic grid (this study). Faults onshore from Boehner and Giles (1986), Raeside and Barr (1992), and Barr et al. (1998): AF, Aspy Fault; BF, Bateston Fault; BPF, Big Pond Fault; CF, Coxheath Fault; EBF, East Bay Fault; EHSZ, Eastern Highlands Shear Zone; GRF, Georges River Fault; HF, Hollow Fault; HOF, Homeville Fault; MBF, MacAskills Brook Fault; MF, Mountain Fault; WBFZ, Wilkie Brook Fault Zone; WCF, Waddens Cove Fault. R, zones of especially prominent reactivation after deposition of the Morien and Pictou groups. Note that fault dips in the reactivated zones are those inferred at the time of earlier extensional basin development.



by Raeside and Barr (1992), that bounds Carboniferous rocks along the eastern margin of the Cape Breton Highlands (Fig. 15). Unit 2 oversteps the fault zone onto a broad basement area here termed the Smoky Mountain High. The half-graben may have a complex structure, as unit 1 reflectors show southerly dips on line 4103-83, but northerly dips on both line 4101-83 and the Lithoprobe line farther offshore. This may be due to fault complications, as the depocentre lies adjacent to the Eastern Highlands Shear Zone (Barr et al. 1995) and other faults in the Ingonish area (Fig. 15) which cut Carboniferous strata.

The northern boundary of the Sydney Basin is marked by a complex fault zone that can be projected into both Cape Breton Island and Newfoundland and includes the Hollow, Aspy, Long Range, Cape Ray, and Wilkie Brook faults (Figs. 1, 15). Upper Paleozoic strata thicken north of the Cape Ray Fault Zone into the Cape Ray Graben, bordered to the north by the Cabot Fault Zone (Langdon and Hall 1994) (Fig. 15). The Searston Graben lies between the Cabot and Hollow fault zones. Seismic analysis by Langdon and Hall (1994), supplemented by information from southwestern Newfoundland, suggests that the Horton Group is present at depth in both grabens and that Windsor evaporites are present in the Searston Graben. Marillier et al. (1989) showed both basins as Horton depocentres in their Lithoprobe line interpretation. In northern Cape Breton, Horton strata are prominent in the Cabot Sub-basin of Hamblin and Rust (1989), interpreted as a half-graben. The Cape Ray Fault was active during the lower Paleozoic (Dube et al. 1996), as was the Cabot Fault Zone, which was strongly reactivated during the Late Carboniferous to Permian (Langdon and Hall 1994).

Timing of fault activity and thermal subsidence

The triangular geometry of unit 1 (largely Horton Group), with an upward decrease of reflector inclination, indicates that the master fault zones were active during deposition in the Tournaisian. In contrast, the synformal and wing geometry of unit 2 (largely Windsor and Mabou groups) suggests cessation of fault control and the onset of thermal relaxation during the Visean to early Namurian, as suggested for other parts of the Maritimes Basin (Durling and Marillier 1993; St. Peter 1993). Strata of unit 2 were initially deposited near the master faults but later overstepped onto basement rocks beyond the master fault, as noted onshore. An important contributing factor to widespread Windsor deposition was a global sea-level rise, which culminated in the Visean (Hallam 1984).

Mid-Carboniferous deformation and basin inversion

In seismic lines, some faults appear to cut only unit 1, whereas others additionally appear to cut unit 2, but not unit 3 (Fig. 8, shotpoints 900–1100; Fig. 10, shotpoints 1100–2100; Fig. 13, shotpoints 700–1300). These observations suggest that some tectonic activity accompanied and (or) followed Windsor and Mabou deposition but preceded deposition of the Morien and Pictou groups, in accord with onshore mapping. Master fault zones may have been reactivated during the mid-Carboniferous, but this is difficult to prove from the seismic profiles. The angular unconformity present onshore and represented by surface C indicates that basin inversion preceded deposition of unit 3. As noted above, this tectonic episode corresponds with the Alleghanian orogeny in the United States Appalachians.

Late Carboniferous basin

Seismic features and depocentre geometry

From the late Westphalian B to the Stephanian – Early Permian, renewed subsidence led to the deposition of the Morien and Pictou groups (unit 3). These strata constitute the Sydney Basin sensu stricto, and unit 3 reflectors blanket the entire study area (Figs. 8, 14). The Late Carboniferous basin may have been saucer-shaped in a northeast–southwest cross section, as the strata thicken away from the Cape Breton coast and appear to dip basinward away from the Newfoundland coast, although multiples preclude a more detailed analysis. In the Cape Ray Graben, Langdon and Hall (1994) showed a northwestward-thickening wedge of strata above their Namurian–Westphalian unconformity, onlapping the Cape Ray Fault Zone. This stratal wedge is imaged in unit 3 at the northern end of the Lithoprobe line (Fig. 14, shotpoints 2400–2700), but the age of the strata is not known.

The coal-measure reflector package of the Sydney Mines Formation forms a distinctive regional marker. Its thickness ranges from 0.2 to 0.4 s TWT (~300–600 m) and its depth near the Cape Breton coast is typically 0.4–1.0 s TWT (~600–1500 m). The package is shallower over basement highs (0.5–0.6 s TWT, ~700–900 m depth) and appears less prominent towards the northwest (Figs. 8, 9). Near Newfoundland, the coal measures overlie basement rocks in Placentia Bay (King et al. 1986), although they are not known under the Burin Platform (Pascucci et al. 1999).

Unit 3 strata below the coal measures are correlated with the South Bar Formation and vary in thickness locally. Figure 12 illustrates an area where they are relatively thick within a synform (shotpoints 600–900) and thin northwestward onto the Smoky Mountain High north of the St. Anns Fault Zone (shotpoints 1300–1600). A similar thinning is observed onto the North Sydney High (Fig. 13, shotpoints 100–300). Hacquebard (1983) divided the Sydney Basin, at the level of the Morien Group, into the Glace Bay and Ingonish subbasins, separated by the North Sydney High (Boisdale Anticline). Gravity data (Loncarevic et al. 1989) show that the high forms part of a positive gravity anomaly bordered on both sides by gravity lows. The rocks that contribute to the lows are not known with certainty, but the gravity data support the existence of Upper Carboniferous subbasins. However, the high was probably not a strong paleotopographic feature, as the coal-measure reflector package is evident on both sides and over its crest, and thinning of the package over the high could not be confirmed. We note later that the present structural expression of the high is partly due to a later tectonic event.

Causes of basinal subsidence

The near-parallel pattern of unit 3 reflectors across the basin indicates that renewed subsidence was not related to the previously active master faults. The blanket stratal geometry suggests minimal intrabasinal tectonism and extension of the basin margins beyond their previous limits. These features are in accord with models of posttectonic thermal subsidence (Bradley 1982), and Leighton and Kolata (1991) considered the basin's Late Carboniferous subsidence phase to be cratonic in style. The onlap of unit 3 onto Scatarie Ridge (Fig. 14) and coal-bearing strata onto basement rocks in Placentia Bay is consistent with thermal relaxation.

As noted by Gibling et al. (1987), the Upper Carboniferous strata occupy the "angle" between regional fault zones that experienced Upper Carboniferous strike-slip activity: the Hollow, Long Range, and Cape Ray fault system in the north and the Cobequid–Chedabucto fault system in the south (Fig. 1). These faults may have promoted regional subsidence, possibly with an extensional contribution from the mid-crustal detachment (see Quinlan 1988). The stratal wedge above the Namurian–Westphalian unconformity in the Cape Ray Graben provides some evidence that fault zones in the Cabot Strait influenced depositional patterns.

Thicker Morien strata accumulated in paleotopographic lows that correspond to the Glace Bay, Sydney Harbour, and Boularderie synclines (Boehner and Giles 1986). These areas of thicker fill appear to overlie the Marconi, Cranberry, and Aconi half-grabens, suggesting the influence of Early to mid Carboniferous paleotopography on later deposition. The northeasterly paleoflow during Morien deposition (Gibling et al. 1992) also reflects in part the influence of basement uplifts and earlier depositional axes.

The basal Morien unconformity has equivalents in the Cabot Strait (Langdon and Hall 1994) and under the Gulf of St. Lawrence (Rehill 1996; Giles 1999). It has been linked to Alleghanian deformation (Gibling 1995) and can be broadly correlated with the Mississippian–Pennsylvanian unconformity of the Appalachian Basin. As noted by Gibling et al. (1992), the predominantly northeasterly paleoflow in the Upper Carboniferous and Permian in the Sydney Basin and across Atlantic Canada is in accord with drainage sources in the rising Appalachian mountain chain.

Post-Carboniferous deformation

Unit 3 is strongly deformed in three areas (R in Fig. 15), with steep dips and the imposition of a prominent antiformal structure. Two of these antiforms are evident in the Lithoprobe line along the North Sydney Fault Zone near well P-05 (Fig. 14, shotpoints 1400–1500) and the Donkin Fault Zone (shotpoints 500–600); the Dominion Fault Zone was probably reactivated also, although there is no seismic evidence. The third antiform is associated with the Cabot Fault Zone. Interpretations of the deformation history presented here must be viewed as provisional in view of the low quality of the profiles, especially as chaotic seismic patterns may represent the influence of features out of the plane of the seismic profiles.

North Sydney Fault Zone

The North Sydney High is the best imaged antiform. It is about 6–10 km wide and, at the level of the coal measures, is symmetric to gently asymmetric (Fig. 9, shotpoints 400–800; Fig. 13, shotpoints 1–300) or asymmetric with one flank very steep and the other gently inclined (Fig. 12, shotpoints 200–600). It is mainly steeper on its southeastern side but locally on its northwestern side. In places, it is faulted and loses much of its topographic continuity (Fig. 11, shotpoints 2400–2100) but, on a larger scale, it forms a linear feature that extends for tens of kilometres in a northeasterly direction. Below the antiform, units 2 and 3 are strongly deformed, and unit 2 appears chaotic in places, completely losing its normal character of well-marked reflectors (Fig. 9, shotpoint 600; Fig. 11, shotpoints 400–600). Associated faults appear to cut much of unit 3, suggesting that fault activity postdated deposition of both the Morien and Pictou groups and constraining fault activity to Stephanian – Early Permian or later.

Two deformational styles are identified. A probable *inverted half-graben* is seen in line 4099-83 (Fig. 13, shotpoint 200). In the upper part of unit 2 and in unit 3, reflectors dip away from the bounding fault and are deformed into a gently asymmetric antiform. Small faults appear to branch from the southern side of the master fault. Similar geometries described from seismic lines by Roberts (1989) and from experiments by Buchanan and McClay (1991) were interpreted to indicate half-graben inversion through reactivation of the master fault as a reverse or thrust fault. If the fault is too steeply inclined, shortcut faults with shallower dip develop (Cooper et al. 1989), and small branch faults inferred in line 4099-83 may have formed in this way.

A probable *positive flower structure* is illustrated in Fig. 12 (shotpoints 400–600), with additional examples in Fig. 9 (shotpoints 1600–1800) and Fig. 10 (shotpoints 2100–2400). The structure is an asymmetric antiform with a steep southeast side and chaotic acoustic character in units 1 and 2. The antiform does not appear to correspond with basement topography. The structure appears to have reactivated preexisting faults, as indicated by its occurrence adjacent to thicker regions of unit 1 (Fig. 9). However, in some areas, an antiform was apparently generated without precursor faults (Fig. 9, shotpoints 1600–1800; Fig. 11), although deformation may have reactivated preexisting lines of weakness in the basement rocks below the level of seismic resolution. Imaged dislocations suggest that faults diverge upwards and show reverse separation.

A positive flower structure is a linear antiform bounded longitudinally along its flanks by upward- and outward-diverging faults that normally have reverse separation (Harding and Lowell 1979; Harding 1985). A chaotic appearance is commonly observed on seismic lines due to dispersion of the reflected energy through the complex structure (Harding 1985). Parts of the North Sydney High appear to correspond closely with these features. Flower structures are generally associated with wrench faults and are promoted by a component of convergence normal to the wrench fault (Harding 1985). Harding (1985) noted the difficulty of distinguishing positive flower structures from contractional fault blocks (Stearns 1978), especially where seismic resolution is low.

As Early Carboniferous fault-bounded basins are present offshore, a contractional fault-block model could be appropriate. Flower structures can be identified by their lateral persistence and abrupt changes in profile appearance (Harding 1985), both of which are suggested for the North Sydney High. In contrast, contractional fault blocks show a consistent upthrown side, discontinuities along strike due to fault offsets, and folds above fault zones that are harmonic with the underlying basement. The latter criterion is not suggested by the relationships interpreted in line 4105-83 (Fig. 11).

Donkin Fault Zone

The Donkin Fault Zone is too poorly imaged on industry lines to allow structural analysis, but the antiformal structure of unit 3 corresponds to a positive magnetic anomaly offshore (Loncarevic et al. 1989; Jansa et al. 1993), suggesting relative elevation of basement rocks. From the Lithoprobe line, the structural zone could be interpreted as a flower structure or a diapir, but there in no other evidence of diapirs in this area. The structure may be a reactivated fault within the Marconi Half-graben (Fig. 14). The offshore extent of the structure is not known.

Faults with predominantly reverse separation are known in the Perce Anticline and Morien Syncline (Fig. 3) where the Sydney Mines Formation has unusually steep dips (Haites 1951; Courtney 1996). The Perce Anticline appears to be the onshore extension of the Donkin Fault Zone. No single major fault is associated with the anticline, but the structure is approximately aligned with the Big Pond, Macaskills Brook, and Homeville faults (Fig. 3). One or more of these faults may run inland into the prominent L'Archeveque – Mira Bay fault system which was active within the Mira Terrane in the latest Precambrian (MacDonald and Barr 1993). Close to this zone, the basin-bounding Bateston Fault juxtaposes the Sydney Mines Formation against older rocks, with local reverse motion.

Dominion Fault Zone

The Dominion Fault Zone probably correlates with the prominent Bridgeport Anticline (Fig. 3), where Morien strata have been strongly deformed. It is poorly imaged in industry lines, but unit 3 on the Lithoprobe line appears to show a weak antiformal structure over the fault zone (Fig. 14).

Cabot Fault Zone

Positive flower structures and basin-inversion effects were inferred by Langdon and Hall (1994) along strands of the Cabot fault system in the Cabot Strait which they interpreted as a strike-slip fault system with a transpressive dextral component. Flower structures are well imaged on their line 81-1121 in association with the fault system and appear to deform all the upper Paleozoic strata. Wright et al. (1996) identified positive flower structures in the Deer Lake Basin of western Newfoundland, also linked to strike-slip motion on the faults, which they inferred to have been active during the Late Carboniferous.

Timing of deformation

The structure of reactivated zones both onshore and offshore implies a compressional or transpressional event, but there is no direct evidence for its timing. Vitrinite structure in coals at the Cape Perce and Bridgeport anticlines suggests that coalification took place while the beds were flat lying and that the bulk of the tilting along these structures postdated coalification (W. Langenberg, personal communication, 1999). Coalification was probably complete by the onset of cooling, documented as mid-Triassic or earlier from fission-track analysis and probably linked to exhumation. If this reasoning is valid, Permian or Triassic deformation is possible. However, some later coalification is possible if the onshore coal measures were buried by a thick Cretaceous section, implying late Mesozoic or Cenozoic deformation.

Our observations provide the first analysis of an important tectonic phase at Sydney, which we term the *Donkin Episode* after an area where its effects are prominent. Similar effects may have been much more widespread in Atlantic Canada than is currently recognized. Permian compressional events linked to continental collision are known in the northern Appalachian Orogen, and an Early Jurassic or younger compressional event is known in the dominantly extensional Fundy Basin. Our preference is for a Permian age for deformation in the Sydney Basin, based on timing constraints and the profound effects of Permian events elsewhere. It seems improbable that Mesozoic compression could have produced effects far north of the extensional basins.

Evaporite movement

Salt-related structures have not been recognized in the Sydney Basin, apart from a diapir identified by Webb (1973) north of Scatarie Ridge. Local upward tilting and domal reflector patterns (recognized where lines cross) are present in lines D-94, D-98, D-102, and D-106 and associated lines in the northeast (area C in Fig. 2). Diapirs may be present in this area, although the seismic lines are of too poor quality to confirm the existence of Windsor strata at depth and to show links with faults.

Bedrock–cover relations

The Precambrian and lower Paleozoic basement of Cape Breton and Newfoundland contains important fault zones, some of which separate terranes that amalgamated prior to or during the Acadian orogeny (Barr et al. 1995). Two of these boundaries correspond closely with lower-crustal discontinuities (Fig. 1). An important question is the extent to which these preexisting lines of weakness governed subsequent tectonic development.

The Bras d'Or – Mira boundary was placed by Barr et al. (1995) at the Georges River Fault, probably correlative with the North Sydney Fault Zone. White and Barr (1998) noted that extension associated with the McAdams Lake Formation was controlled by the position of this boundary. During the Early Carboniferous, the North Sydney Fault Zone was an extensional fault system which was reactivated after Morien and Pictou deposition. Farther offshore, Marillier et al. (1989) and Loncarevic et al. (1989) inferred a near-vertical break between the deep-crustal Central and Avalon blocks along the line of the terrane boundary. However, Barr et al. (1998) noted that the Moho is not offset along Lithoprobe line 86-5, and suggested that a component of thrusting was involved with block amalgamation. Barr et al. (1995) suggested that the terrane boundary in Cape Breton is equivalent to the Hermitage flexure belt that borders the Avalon Terrane in Newfoundland (Fig. 1). The Dover Fault, closely related to the Hermitage zone, was imaged in a Lithoprobe line north of Newfoundland, where it appears to be a near-vertical structure that penetrates the crust (Keen et al. 1986). Local reactivation as a transpressive feature during the latest Paleozoic or the Mesozoic might explain some aspects of this terrane boundary.

The Aspy – Bras d'Or terrane boundary is marked by the Eastern Highlands Shear Zone in Cape Breton (Fig. 15) (Barr et al. 1995), but Devonian intrusions have affected the expression of the boundary, which probably runs offshore through fault systems near Ingonish. Several Early Carboniferous extensional faults offshore may correlate with this zone. The Blair River – Aspy terrane boundary, which also approximates the Grenville–Central lower crustal boundary, was the site of extensional faulting and subsequent mid-Late Carboniferous and younger deformation along the Hollow Fault and related structures (Langdon and Hall 1994).

The Donkin Fault Zone (Fig. 15), a site of strong late-stage deformation, may correlate with the L'Archeveque – Mira Bay fault zone of the Mira Terrane, itself a composite Neoproterozoic terrane (Barr et al. 1998). Faults of this zone were active during Carboniferous subsidence of the Glengarry and Loch Lomond basins (Boehner and Prime 1993). The Bateston Fault (Fig. 3), a branch of the Mira Bay fault zone, underwent strong deformation after Morien deposition.

We infer that preexisting lines of weakness, including terrane boundaries, strongly influenced later tectonic development in the Sydney Basin. Reactivation of these lines in the latest Paleozoic or Mesozoic may have influenced basement rocks onshore in Nova Scotia and Newfoundland where evidence for younger events has rarely been adduced (see Miller and Singh 1995).

Implications for hydrocarbon systems

Small amounts of hydrocarbons are present at many levels in the Sydney Basin fill. Source rocks in the form of organic-rich shales, limestones, and coals are known in the McAdams Lake Formation, the Windsor Group (especially the Macumber Formation), the Mabou Group, and at many levels in the Morien Group. A variety of stratigraphic and structural traps for hydrocarbons are possible. Windsor evaporites may form important seals locally, although bedded evaporites are not prominent. Maturation levels of Morien Group coals and shales are in the hydrocarbon-generation zone (Hacquebard and Donaldson 1970; Hacquebard 1983; Gibling and Kalkreuth 1991), as are Horton source rocks in Cape Breton (Utting and Hamblin 1991). Vitrinite reflectance values for strata low in the P-05 well approach 1.8% (Cooper et al. 1974), in the overmature zone, but it is not known if these values are representative. Several prerequisites for hydrocarbon systems are clearly fulfilled.

The Sydney Basin has undergone a *polycyclic* late Paleozoic to Cenozoic history (Fig. 16). Subsidence phases in the mid-Devonian, Early Carboniferous, Late Carboniferous, and Cretaceous were interspersed with periods of deformation and (or) basin inversion. Thus, McAdams Lake source rocks may have undergone four burial periods, each of which could have caused hydrocarbon generation. Intervening deformation events could have breached preexisting reservoirs or created new structural traps for hydrocarbons generated later. The basin probably reached its maximum burial depth during the Early Permian, and this poses problems for the long-term survival of hydrocarbon accumulations, especially as the Donkin Episode of deformation could have promoted fluid escape. Cretaceous subsidence and maturation may have been important, and the presence of Cretaceous volcanics on Scatarie Ridge (Fig. 1) suggests a local thermal event. Prolonged exhumation of the basin fill commenced in the early Mesozoic or earlier and has been an important factor in bringing potential reservoirs to relatively shallow depths. This brief account serves to illustrate the complexity of the basin's history, and careful analysis will be required if hydrocarbon systems are to be evaluated effectively.

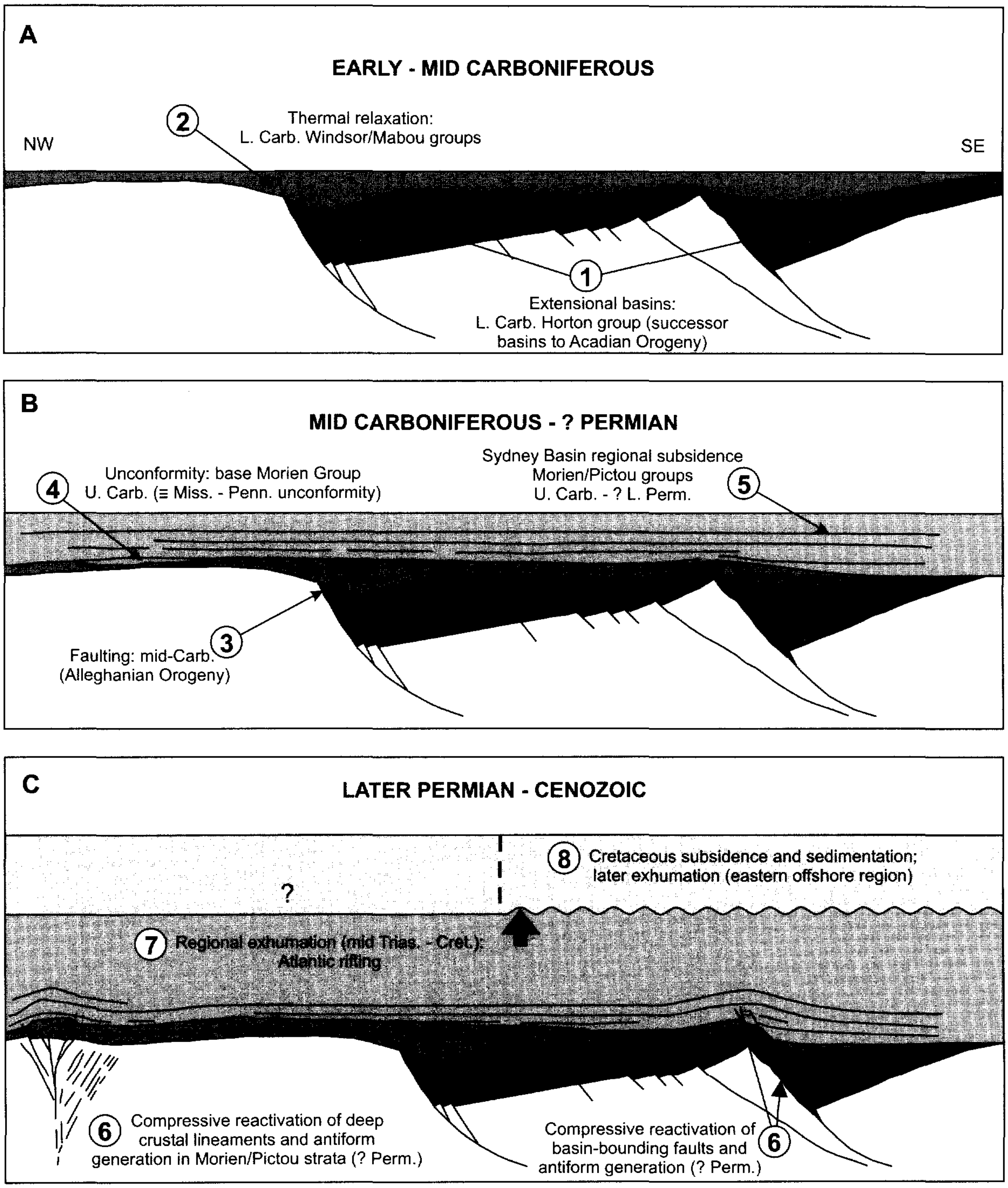
Conclusions

The Sydney Basin of Atlantic Canada has undergone a polycyclic late Paleozoic to Cenozoic history, as indicated from seismic analysis linked to outcrops in Nova Scotia and Newfoundland. As a result of Mesozoic to Cenozoic exhumation, the lower basinal fill now lies at moderate depths. We document a suite of extensional basins filled largely with Lower Carboniferous rocks of the Horton Group and bordered by south-dipping master fault zones (Fig. 16A). The faults are linked to a mid-crustal detachment that may reflect relaxation of northward-directed Acadian thrusts. The overlying Windsor and Mabou groups overstep the Horton Group to rest upon basement rocks as part of a thermal relaxation phase (Fig. 16A) and a eustatic rise.

The Namurian–Westphalian unconformity, which underlies the Morien Group onshore, has basinwide significance and is associated with mid-Carboniferous tectonic activity correlative with the Alleghanian orogeny. This deformation reactivated some extensional faults and inverted some depocentres (Fig. 16B). Subsidence recommenced during the Late Carboniferous, when an extensive basin covered the numerous Early Carboniferous depocentres. A reflector package associated with the Morien Group coal measures appears to be near basinwide and reaches depths of ~1.5 km or more. Coal-measure strata overstep older strata to rest upon basement rocks at several localities. Basin subsidence may reflect thermal relaxation and fault activity in the Cabot Strait.

After coalification was complete, the coal measures underwent local compressive deformation (Fig. 16C), probably during the Permian when the final stages of Pangean assembly were accompanied by tectonism elsewhere in the Appalachians. Mesozoic deformation is considered less probable.

Fig. 16. Major events in the Early Carboniferous to Cenozoic history of the Sydney Basin. Note that the basal Horton Group could be Late Devonian in age, by comparison with other parts of the Maritimes Basin, and that the mid-Devonian McAdams Lake Formation is present onshore but was not identified in seismic analysis (see text).



This deformation phase has not previously been investigated in the Sydney Basin and forms part of a little known tectonic episode in Atlantic Canada. Reactivation of older structural lineaments, including terrane boundaries, is an important aspect of the basin's history and may have modified profoundly the structural expression of some lineaments. Cretaceous subsidence affected parts of the basin, with local volcanism.

The Sydney Basin is in reality a composite depocentre that comprises superimposed basin suites of varied style and origin. Its polycyclic history, with alternate subsidence and inversion, implies that source rocks have undergone a complex history, possibly with several phases of hydrocarbon generation. There were numerous opportunities for creation and destruction of hydrocarbon traps.

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