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Tracking sea bed topography in the Jurassic. The Lotena Group in the Sierra de la Vaca Muerta (Neuquén Basin, Argentina)

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ABSTRACT

The Lotena Group is a clastic to evaporitic unit up to 650 m thick that accumulated during the Middle to Late Jurassic in the Neuquén Basin, western Argentina. Extensive field work carried out in the Sierra de la Vaca Muerta and Arroyo Covunco areas, including the measurement of seven detailed stratigraphic sections and geological mapping allow the discrimination of six unconformity-bounded units or sequences. The first sequence is composed of red beds and evaporites belonging to the Tábanos Formation that unconformably overlies strata of the Lower to Middle Jurassic Cuyo Group. Sequences 2 to 5 are shallow marine and display a basal sandstone interval attributed to confined shelfal sandstone lobes. These grade vertically into unconfined shelfal sandstone lobes, and terminate with carbonate deposits. The basal interval is restricted to the thickest areas of each sequence, a relationship attributed to structural relief. Sequence 6 has a very irregular shape and strongly truncates the underlying deposits. It is composed almost entirely of massive carbonate strata that were deposited by density currents. Facies analysis and stratigraphic mapping suggest periodic recycling of previous accumulations. Stratigraphic evidence suggests that the Lotena Group in the Sierra de la Vaca Muerta and adjacent areas probably accumulated over a tectonically unstable basement. Sequences 1, 2 and 3 display evidence of accumulation in an extensional tectonic setting, while sequences 4, 5 and 6 experienced a northward shift of their depocentres associated with extensive erosional truncation of the marginal areas, suggesting that accumulation was affected by early stages of growth of the Covunco anticline

KEYWORDS **Lotena Formation. Contained flows. Jurassic. Neuquén Basin.**

INTRODUCTION

The existence of very thick structureless to laminated sandstones has been reported in several papers (Elliot et al., 1985; Sinclair, 1992; Baruffini et al., 1994; Marjanac, 1996; Zavala et al., 2002). Their origin has been related to the gravitational collapse of unsteady turbulent flows having high suspended load (Middleton and Hampton, 1976) or, more recently, to the progressive deposition from long-lived underflows (Kuenen and Menard, 1952; Sanders, 1965; Bruhn, 1994; Kneller and Branney, 1995). These long-lived underflows commonly originate at a river mouth when a sediment-laden fluvial discharge enters a standing body of water (Mulder and Alexander (2001), thus resulting in a sustained hyperpycnal flow with deposits having facies and facies-tracts which are at present poorly understood. When these subaqueous sand-bearing currents run into enclosed bathymetric deeps, they underwent a rapid suspension collapse (Pickering and Hiscott, 1985), resulting in a "contained" turbidite and the local deposition of very thick sandstone beds. The thickness and distribution of these sandstone bodies can therefore be used as a proxy for the sea bed bathymetry, allowing also to track the sea bed deformation at time of deposition (Haughton, 2000, 2001).

The present paper addresses on the origin, sequence stratigraphy and evolution of the Jurassic Lotena Group (Fig. 1) based on outcrops in the Sierra de la Vaca Muerta and Los Catutos localities (Fig. 2). In this area, extensive field work included the measurement and description of seven detailed stratigraphic sections (Fig. 3) complemented by a line drawing of horizons using enlarged aerial photographs (Fig. 4). The last approach (photohorizons maps) has been invaluable in regional correlation of the different sections, and to show the large scale geometry of sandstone packages. From this detailed field analysis several very thick (up to 20 m) structureless to laminated sandstone beds have been revealed, which occur in definite positions within the sequence-stratigraphic framework. The occurrence and architecture of these packages have been used to track the sea-bed topography at time of deposition, and allow to make some inferences about the relation between tectonic and sedimentation during the accumulation of the Lotena Group.

STRATIGRAPHY

Located in west-central part of Argentina, the Neuquén basin corresponds to the southern end of a series of marine sedimentary basins developed close to the western margin of Gondwana during the Mesozoic (Fig. 1). This basin has been interpreted as a back-arc basin, with an origin related to the thermal-tectonic collapse of the continental crust behind a stationary magmatic arc during the Late Triassic (Mpodozis and Ramos, 1989). The basin fill is more than 7000 m thick and consists mainly of siliciclastic (and minor carbonatic) sediments (Fig. 1) that accumulated during the Jurassic and Cretaceous. Deposits are mostly shallow marine in origin, and related to a prolonged connection with the paleo-Pacific ocean. Nevertheless, the marine influence was interrupted several times by short periods according to sea-level variations (Mutti et al., 1994; Legarreta, 2002). These periods of marine disconnection are usually characterized by regional unconformities that display in places some angularity, evidencing also a tectonic overprint. Accommodation space increased progressively above the basal unconformity, resulting in the accumulation of a transgressive succession consisting of continental and marine deposits. The Lotena Group (Fig. 1) represents the second marine incursion after the first broad disconnection. The basal unconformity involves a variable span of time and significantly controls the overlying stratigraphy (see for example Zavala, 2002).

In this paper, I will adopt the stratigraphic scheme by Zavala and González (2001) and Zavala (2002) which departs somewhat from the classic stratigraphic column. Based on sedimentologic and stratigraphic evidence, the evaporites and red beds of the Tábanos Formation (Stipanicic, 1966; Dellapé et al., 1979) are included in the basal Lotena Group, and the Auquilco Formation (Schiller, 1912; Weaver, 1931) is assigned to the overlying Mendoza Group (Fig. 1). Therefore, the Lotena Group comprises clastic sediments and (subordinate) carbonates and evaporites that accumulated in the Neuquén Basin during the middle Callovian and Oxfordian. It unconformably overlies marine and continental deposits of the Cuyo Group (Los Molles, Lajas and Challacó formations), and is in turn covered by continental to marine deposits belonging to the base of the Mendoza Group (Fig. 1). The thickness of the unit is highly variable, ranging from a few metres to a maximum of 650 m in the Sierra de la Vaca Muerta.

In the study area, the Lotena Group starts with the evaporites of the Tábanos Formation, is followed by marine sandstones and mudstones of the Lotena Formation (Gulisano et al., 1984), and terminates in the mainly carbonate succession of the La Manga Formation (Stipanicic, 1966; Stipanicic et al., 1975). The existence in some parts of the basin of clastic rocks at the base of the Lotena Formation, consisting of conglomerates, sandstones, and red and gray mudstones lacking a marine fauna, suggests that there was an initial non marine depositional episode restricted to isolated depocentres (Gulisano et al., 1984; Gulisano and Gutierrez Pleimling, 1995; Zavala et al., 2002).

In the studied Sierra de la Vaca Muerta area, six unconformity-bounded units or sequences are recognized. Each sequence can be traced throughout the study area and displays distinctive internal characteristics and evolution. Paleocurrent measurements, mainly from scour marks, suggest a southwest provenance for sequences 2 to 5.

Sequence 1

This sequence unconformably overlies clastic deposits of the Cuyo Group (Lajas Formation). It is composed of evaporites with minor carbonates and red beds, and is assigned to the Tábanos Formation. The unit has an irregular shape that varies in thickness up to 60 m (section 3), but is absent in sections 1, 5 and 7 (Fig. 3). The principal

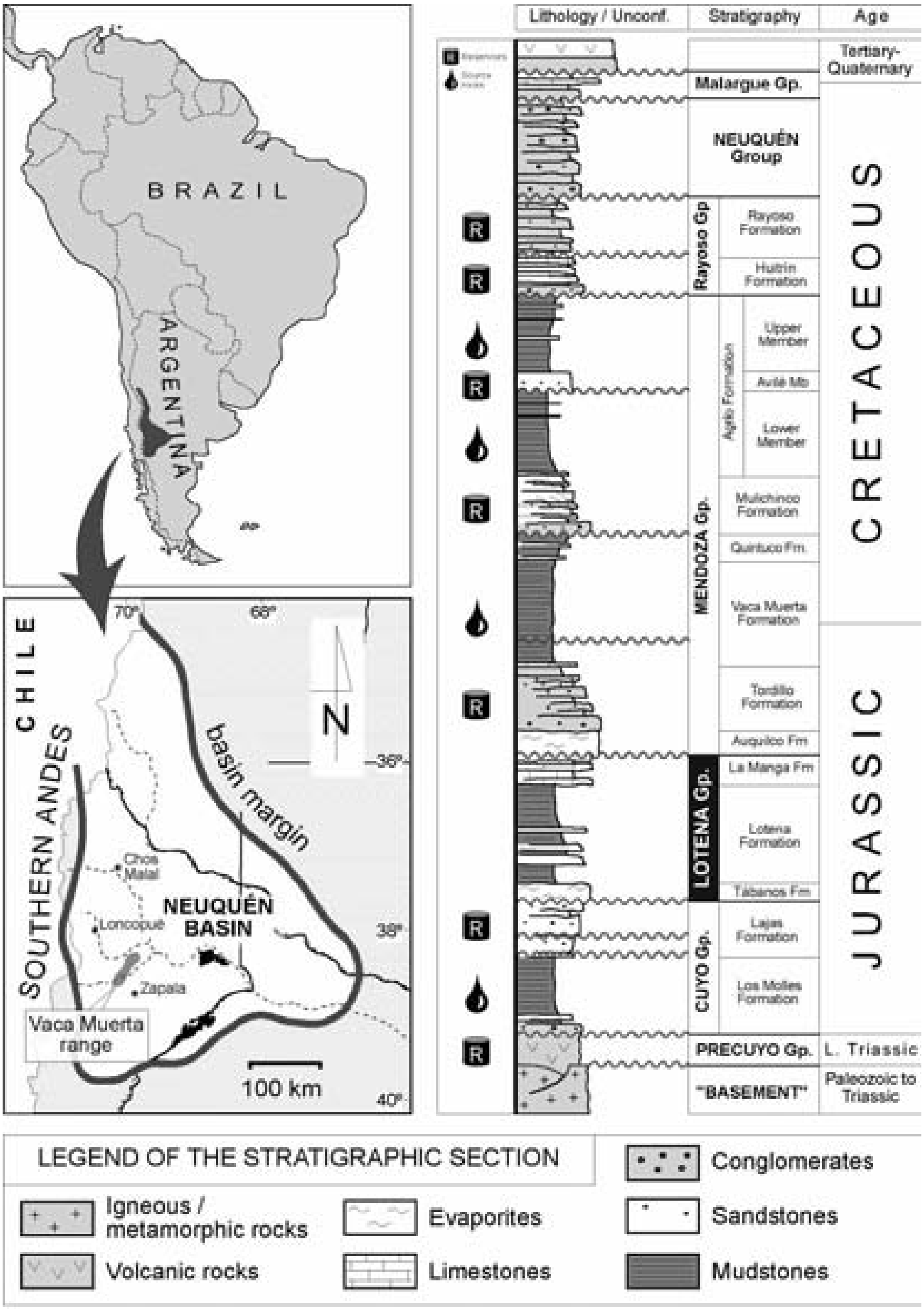

FIGURE 1 **Location map and generalized stratigraphic column of the Neuquén Basin in the western Argentina. The stratigraphic position of the Jurassic Lotena Group in the column is highlighted.**

facies include nodular (chicken-wire) gypsum, that is commonly interbedded with red mudstones and laminated carbonates. Stromatolites are also common. The unit generally has a discrete bed of oolitic limestone located at the base which averages 80 cm thick, with fragments of small bivalves. This sequence marks the beginning of a new transgressive tendency in the basin, because it covers older regressive depositional sequences of the Cuyo Group (Zavala, 2002; Zavala and González, 2001). At the Mallín del Rubio location (section 3), sequence 1 occurs above a

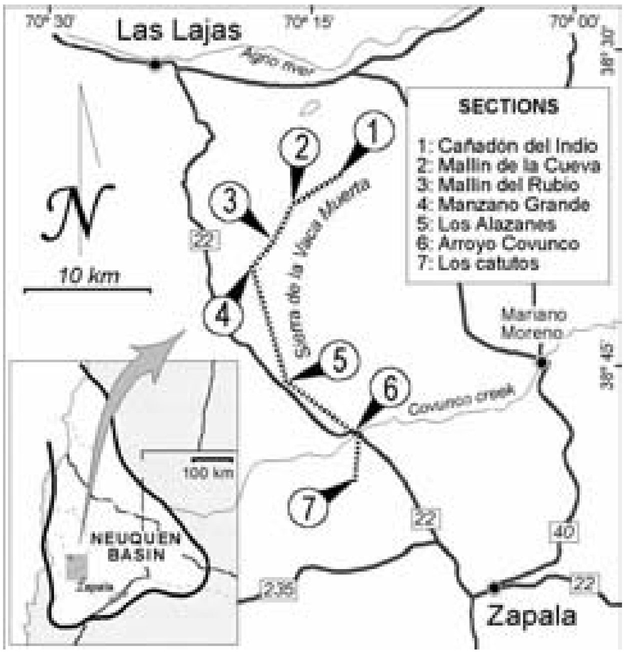

FIGURE 2 | **Location map of the study area, showing measured sections. The dashed line indicate the trace of the cross-section of Fig. 3.**

slight angular unconformity across the Cuyo Group. Abrupt changes in thickness (from 30 to 60 m, Fig. 5) over short distances associated with intense fractured zones affecting the underlying Cuyo Group have been interpreted as related to an initial extensional episode characterized by normal faulting (Zavala, 2002). The location of the maximum thickness, reflecting structural control, and facies changes within the unit suggest deposition over an irregular topography, with the main depocentres probably located in the surroundings of sections 2, 3, 4 and 6.

Sequence 2

This unit reaches its maximum thickness of 325 m in sections 1 and 7, and unconformably covers sequence 1 (Figs. 3, 4, and 6A). It is composed mainly of fine-to medium-grained sandstones and mudstones with scarce marine fossils (mainly ammonoids). A basal metre-thick residual (clast-supported) conglomerate bed is generally present. On a broad scale, the individual sandstone beds are tabular to lenticular, and are commonly massive and very thick (up to 20 m, Figs. 6A and 6B) with floating clay chips (Fig. 6C) and carbonate clasts. Facies analysis suggests a deposition from long-lived sandy high-density turbidity currents (hereafter SHDTC, Figs. 6A and 6C) in a shallow marine environment. The relatively shallow paleodepth is supported by the presence of rare hummocky cross-stratification and wave ripples on top of some sandstone beds. The irregular distribution of this unit and the abnormal thickness of individual sandstone beds can be explained by deposition in structurally controlled depocentres. Onlap relationships of sandstone packages over areas that subside gently are recorded in both measured sections and photohorizons map (Figs. 3 and 4). These onlap relationships are also evident in the panoramic view of Fig. 6A. In the Los Catutos area, this

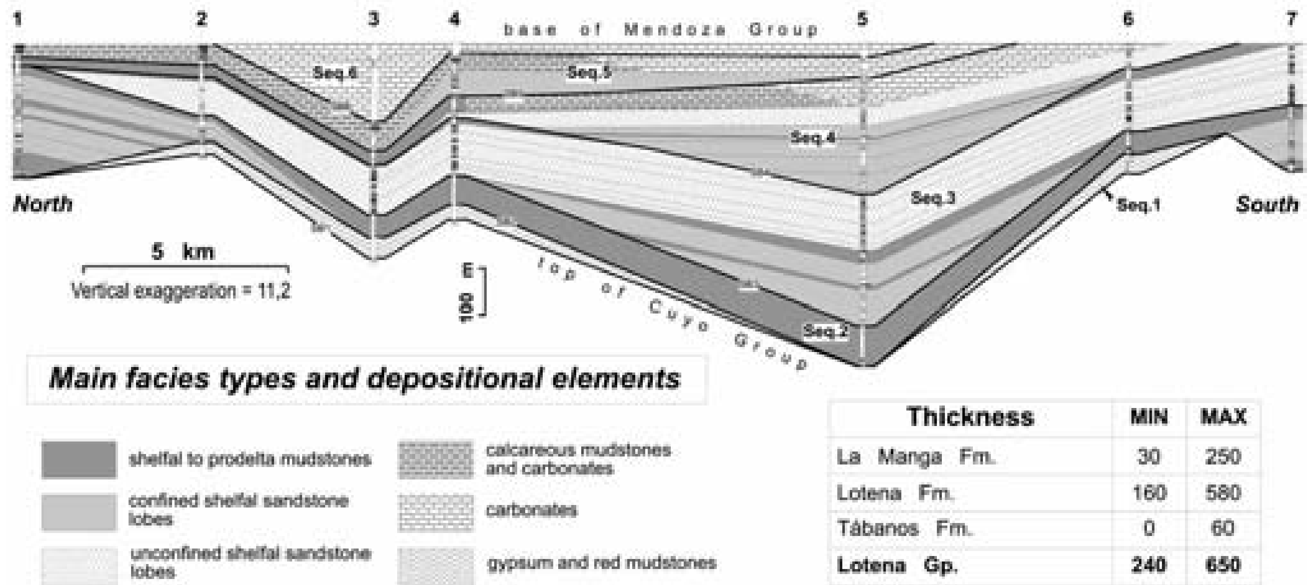

FIGURE 3 | **Stratigraphic cross-section of the Lotena Group in the Sierra de la Vaca Muerta and Los Catutos areas (see location in Fig. 2). Depositional sequences and their constituting facies are indicated. Note that the thickness of the Lotena Group is variable, ranging from 240 to 650 m. SB: sequence boundary.**

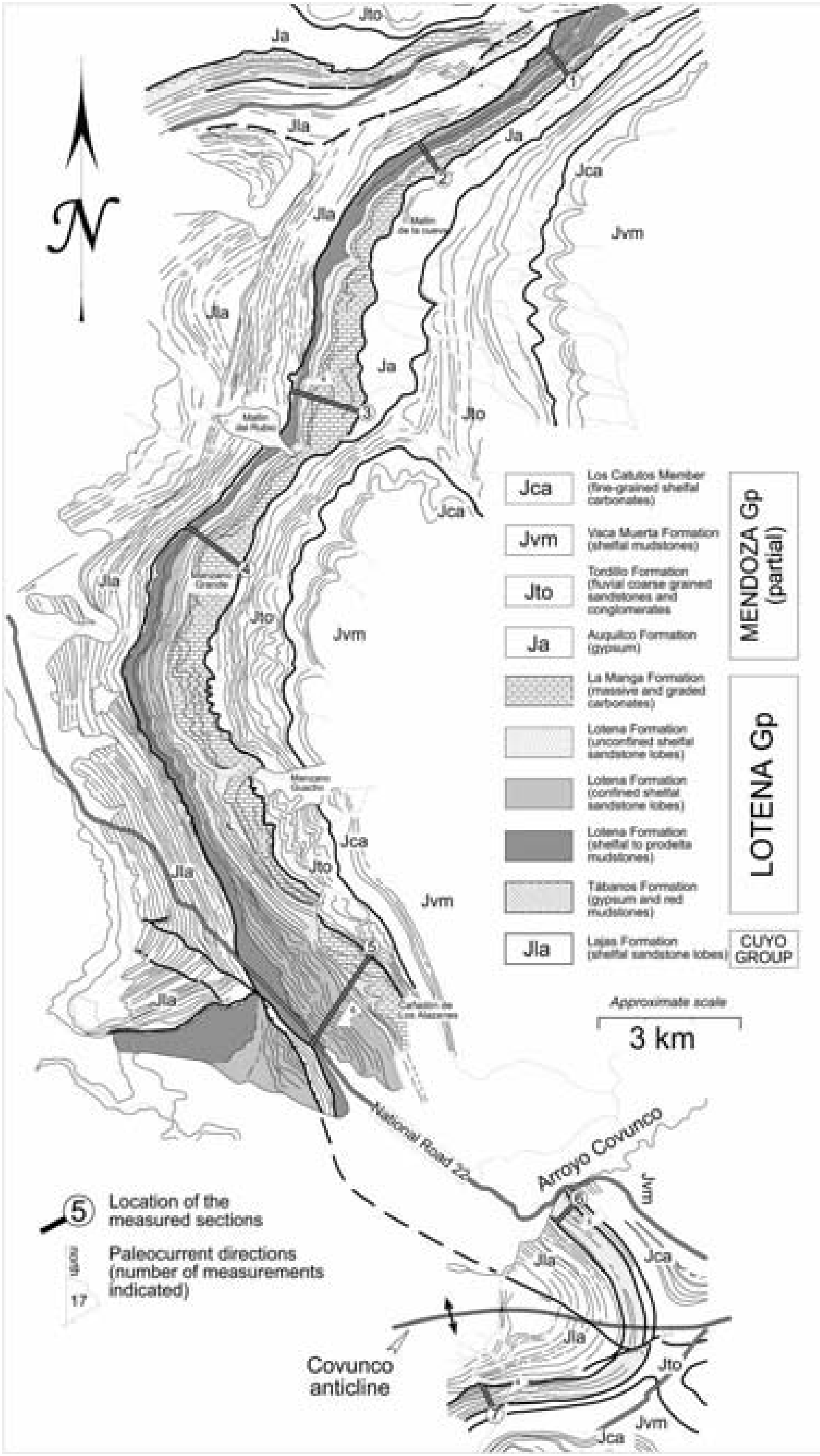

FIGURE 4 **Geologic map of the Jurassic succession that outcrops in the Sierra de la Vaca Muerta and Arroyo Covunco localities. Photohorizons are indicated with thin continuous lines. Note the onlap relationships at the base of the confined shelfal sandstone lobe facies in the vicinity of sections 1, 5 and 7.**

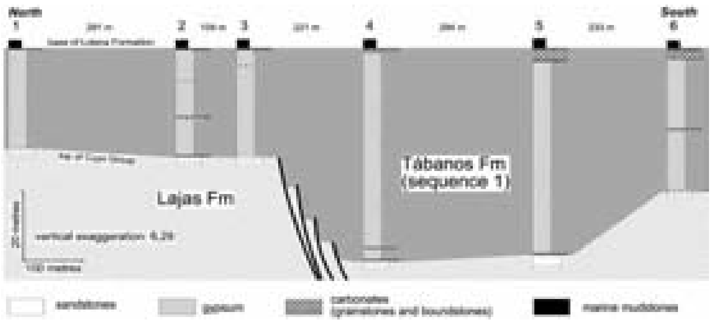

FIGURE 5 | **Detailed cross section of the sequence 1 (Tábanos Formation) in the vicinity of section 3 (Mallín del Rubio). Note the abrupt increase in thickness related to a normal fault affecting the top of the Cuyo Group. Section numbers (1 to 6) refer to local sections. Modified after Zavala (2002).**

sequence fills a tectonic relief characterized by a series of small extensional listric faults that affect the top of the Cuyo Group (Zavala, 2002).

Sequence 3

Similar to sequence 2, sequence 3 is composed of fine to medium-grained sandstones and mudstones with fragments of marine fossils. The unit varies in thickness up to 286 m (measured at section 5, Los Alazanes). Two different kinds of sandstone packages, separated by a mudstone interval, are recognized within the succession (Fig. 3). The lowermost package is composed of massive and very thick (up to 10 m) sandstone beds which are usually amalgamated, and contain floating clay chips and carbonate clasts. This type of sandstone is only recognized in the lowermost part of section 5, and disappears progressively towards the north and south by the depositional onlap and pinchout onto the preceding sequence boundary (SB3, Fig. 3, see also Fig. 4). The second type of package consists of graded massive to structured fine-grained tabular sandstone beds, with individual thickness-

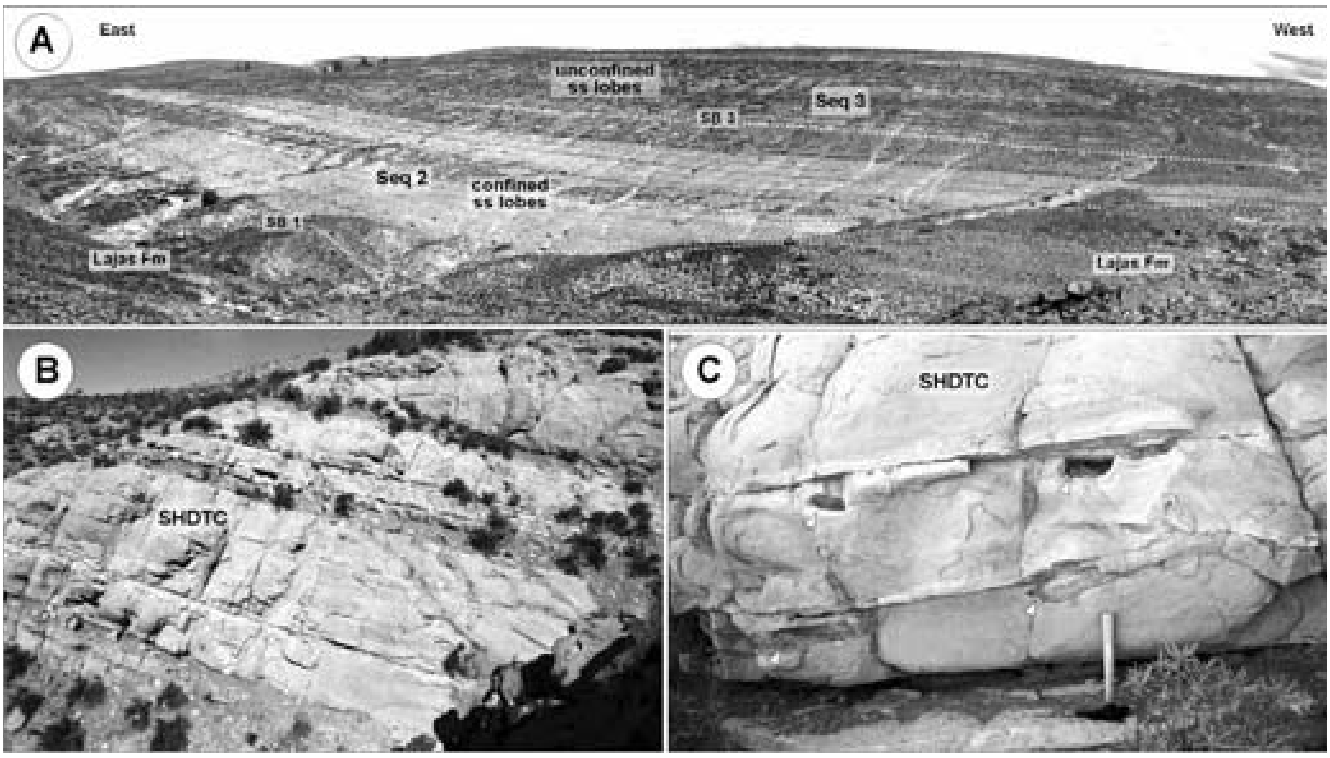

FIGURE 6 | **A) Panoramic view of sequences 2 and 3 in the vicinity of section 7 (Los Catutos). Note the lenticular shape in large scale of the confined shelfal sandstone lobes of sequence 2 and the onlap above the Lajas Formation (on the right). B) Detail of thick massive sandstone beds deposited by long-lived sandy high-density turbidity currents in confined areas. See the geologist on the lower right corner for scale. C) Detail of massive sandstone beds with large floating clasts (arrows). Note their occurrence close to the bed top. SB: sequence boundary.**

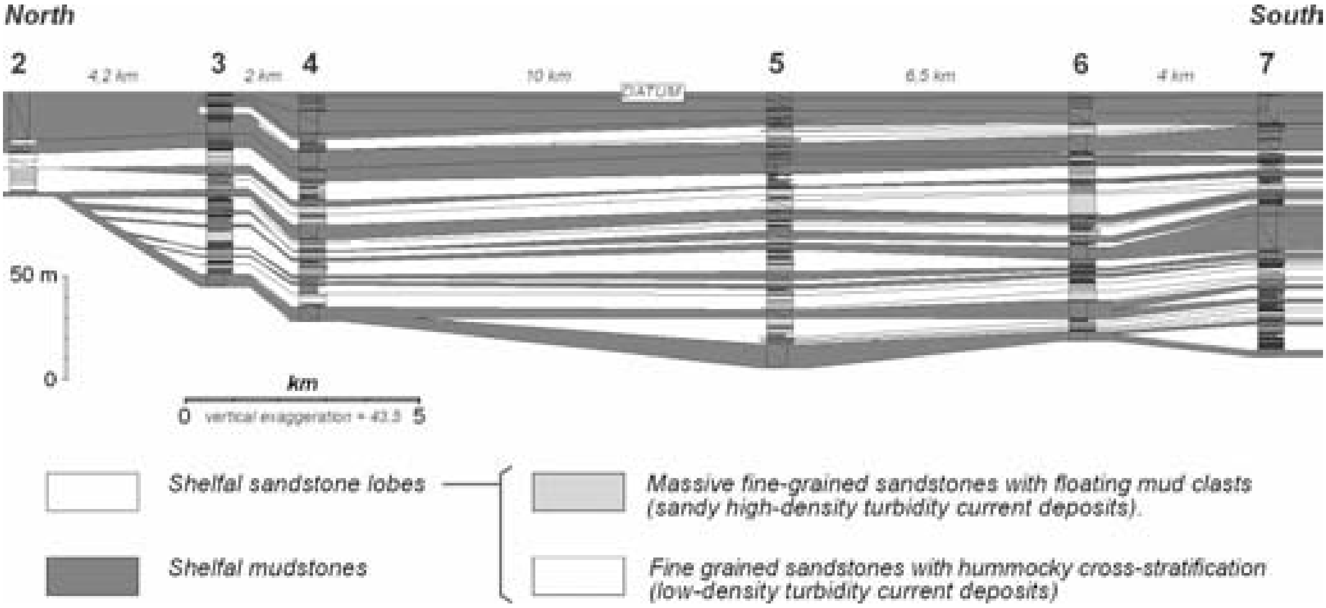

FIGURE 6 | **Detailed cross section of unconfined shelfal sandstone lobes of sequence 3, along a distance of about 26,7 km in a direction roughly perpendicular to paleocurrent directions. These strata are composed of fine-grained and normal-graded sandstone bodies, which appear massive or having hummocky cross-stratification. Paleocurrents are from the southwest. See Fig. 2 for location of the sections.**

es up to 1 m, and interbedded gray mudstones. Although the individual sandstone beds are not very thick, the entire package can be correlated and traced laterally for more than 27 km (Fig. 7). Lateral changes in thickness of individual packages are related to compensation cycles (Mutti and Sonnino, 1981), synsedimentary structural deformation, or a combination of both. Facies analysis (tabular and massive sandstone beds with floating mud clasts) suggests that these strata were probably deposited by unconfined sandy high- to low-density turbidity currents. The sandstone beds are markedly tabular (Figs. 8 and 9A), and are interpreted as shelfal sandstone lobes (in the sense of Mutti et al., 1996). The geometries of these shelfal sandstone lobes resemble turbidite lobes, but differ in some common facies types and paleodepth indicators like the presence of rare hummocky cross-stratification and wave ripples.

Sequence 4

This sequence is thickest in section 5 (254 m), and is composed internally of a basal clastic interval that grades vertically into a carbonate-dominated succession. Facies analysis suggests that deposition started with abnormally thick and massive sandstone beds deposited by sandy high-density turbidity currents (SHDTC) in a confined setting. Like the basal interval of the previous sequence, these deposits accumulated in the preexistent topographic troughs and progressively onlap adjacent topographic highs where they could be absent (for example in sections 4 and 6; Fig. 3). The gradual smoothening of the basin floor led to a progressive lost of flow confinement which resulted in the deposition of unconfined shelfal sandstone lobes. These sandstone lobes are characterized by widespread sandstone beds of discrete thickness, and can be traced for more than 20 km (Fig. 3). The upper part of the sequence 4 is characterized by the intercalation of massive calcareous sandstones and micritic limestones that contain floating bioclasts. These sediments are believed to have accumulated on a carbonate ramp. This carbonate interval grades northward into calcareous mudstones.

Sequence 5

This sequence is composed of a basal clastic interval followed by carbonate deposits. The maximum thickness measured in section 4 is 94 m. The basal clastic interval is composed of very thick (up to 10 m) massive sandstone beds (deposits of SHDTC flows) containing floating clay chips and displaying a lenticular shape regionally with a maximum development in the vicinity of section 4 (Fig. 9B). This interval is overlain sharply by calcareous mudstones that grade into massive and graded micritic carbonates with floating bioclasts (Fig. 9C). The presence of conspicuous grading in some of the carbonate beds, and the common occurrence of floating and projected (above the depositional surface) bioclasts in a carbonate muddy matrix suggest redeposition by high density flows (Shanmugam and Benedict, 1978). These deposits may have been partly cannibalized from the carbonates of the previous sequence. The carbonate interval changes facies towards the north, where it grades into massive (micritic) limestone beds that are interbedded with calcareous mudstones (Fig. 9D).

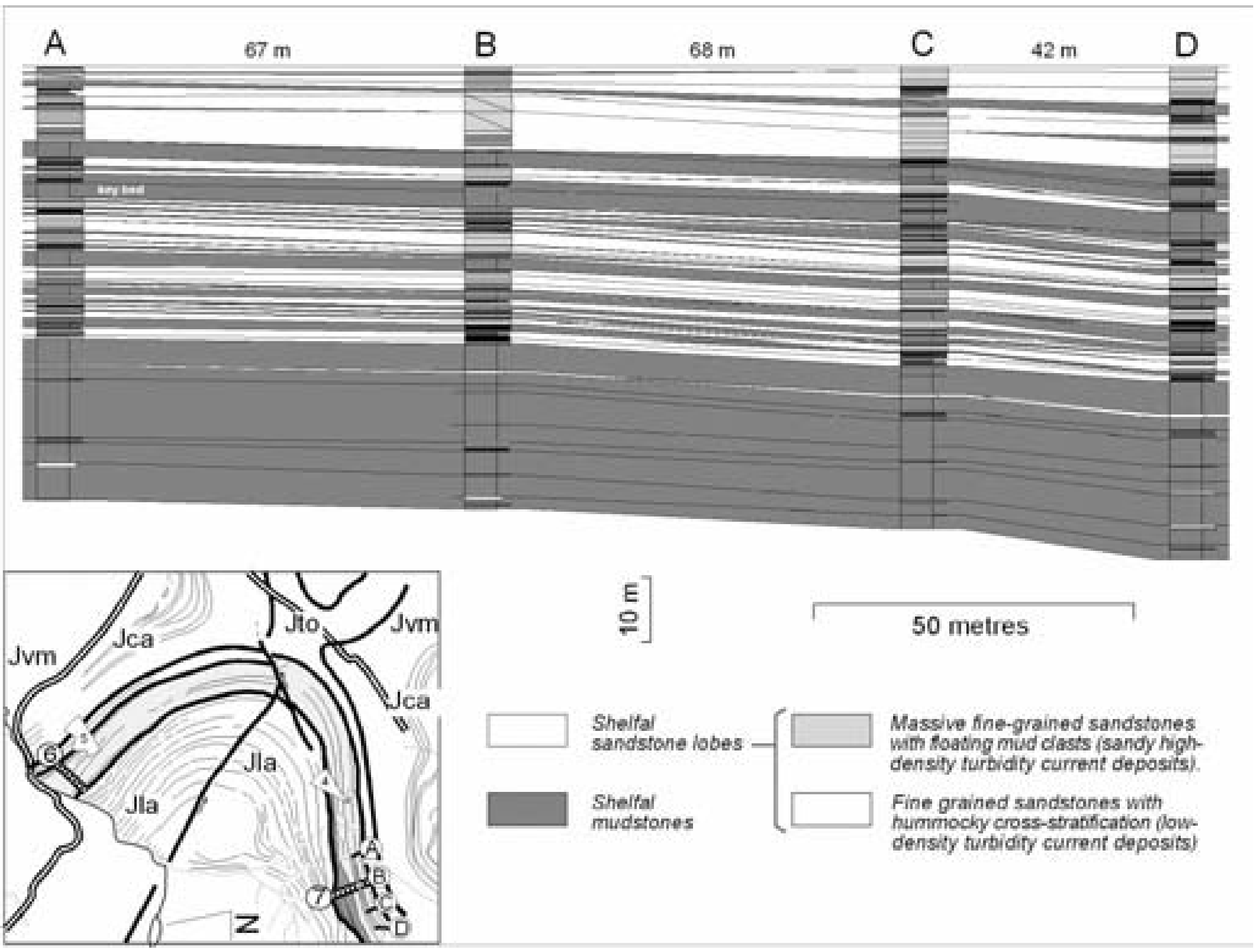

FIGURE 8 | **Detailed cross section of shelfal sandstone lobes of sequence 3 in the vicinity of section 7, showing the main facies types. Note the tabular geometry of most sandstone and mudstone beds. This cross section has not vertical exaggeration. Letters (A-D) refer to local sections, which are indicated in the detailed map "A". This map is a detail of the lower right corner of Fig. 4, with references there.**

Sequence 6

This sequence clearly truncates the previous sequence 5 (Figs. 3 and 9C). It is composed dominantly of massive or crudely graded carbonate beds, with minor interbedded stromatolitic limestones assigned to the La Manga Formation. Sequence 6 has a very irregular shape (Figs. 3 and 9C) and its maximum thickness, measured in section 3, is 193 m. Usually the massive carbonates include floating bioclasts composed of bivalves and corals, which in some places are projected on the upper bedding surface. The bioclasts are randomly oriented and appear to be floating and dispersed in a muddy carbonate matrix. Similar strata in the Ordovician Whitesburg Formation of the southern Appalachians have been interpreted as carbonate debris flows deposited by cohesive freezing (Shanmugam and Benedict, 1978), and related to tectonic pulses that were associated with basin subsidence. No extensive reef deposits have been found anywhere in the succession. The only recognized *in situ* reef is very small (patch-reef?) and has been found in section 6 (Arroyo Covunco). Then, sequence 6 is composed almost entirely of gravitationally resedimented carbonates derived partially from erosion of previous sequences.

CONFINED SHELFAL SANDSTONE LOBES AS A TOOL TO TRACK SEA BED TOPOGRAPHY

The sequence stratigraphy of the Lotena Group in the Sierra de la Vaca Muerta and Covunco areas allows to outline some recurrent characteristics of the unconformity-bounded units. Except for sequences 1 and 6, which are composed almost entirely of evaporites and carbonates, the other four sequences display a distinctive internal stratigraphic pattern. All these sequences have an irregular shape, and show an internal organization distinguished by:

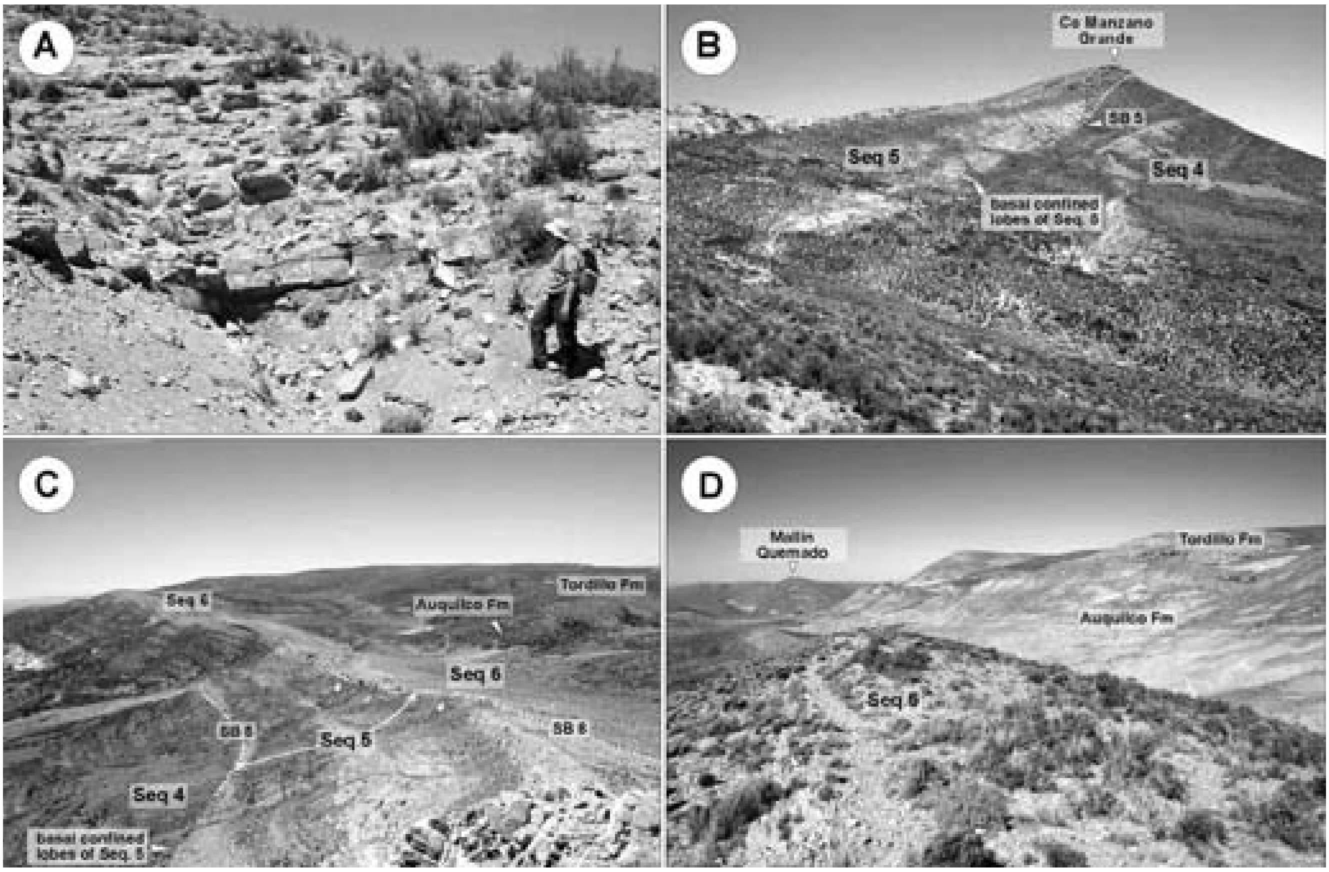

FIGURE 9 **A) Detail of tabular sandstone bodies interpreted as unconfined shelfal sandstone lobes. B) Panoramic view of the boundary between sequences 4 and 5 in the vicinity of Cerro Manzano Grande. Note the lenticular shape of the confined shelfal sandstone lobes located at the base of sequence 5 (indicated). C) Panoramic view from the Cerro Manzano Grande locality towards the north. Note the erosional surface located at the base of sequence 6 (arrows). D) Panoramic view of the unconformity between the sequence 5, La Manga Formation, and the overlying Auquilco Formation in the Cañadón del Indio area. Note the absence here of the carbonates of sequence 6, which are truncated.**

1) A basal interval characterized by very thick (single beds up to 35 m) massive sandstone beds with floating clay chips and carbonate clasts, deposited by long-lived sandy high-density turbidity currents in confined areas (confined shelfal sandstone lobes). These basal intervals are restricted to the thickest parts of the sequence, and progressively pinch out towards the flanks, onlapping areas of topographic or structural relief.

2) An intermediate interval composed of highly continuous tabular sandstone beds (unconfined shelfal sandstone lobes). Although the facies types of individual beds resemble those of the basal interval, the decrease of confinement resulted in a small (up to 2 m) bed thickness.

3) An upper interval dominated by carbonate deposition. This last interval is absent in sequences 2 and 3. These carbonates include massive micritic limestones that grade basinward into calcareous mudstones, small boundstones interpreted as patch reefs and stromatolites, and massive and crudely graded carbonates. This last facies becomes dominant in the uppermost sequences, where it is attribuited to carbonate sediment gravity flows.

The internal evolution of each sequence suggests that the accumulation of the first interval was controlled largely by sea-bed topography during deposition. Recent papers have emphasized the importance of topography in controlling facies of contained turbidites in structurally confined areas (Pickering and Hiscott, 1985; Pantin and Leeder, 1987; Haughton, 1994), and the use of these contained turbidites to track sea-bed deformation and basin migration (Haughton, 2001). Figure 10 shows the geometric distribution of each of the six sequences, and their facies characteristics. The arrows indicate areas of relatively low and high topography during deposition. Sequence 1 has maximum accumulations distinct from the other following five sequences, suggesting the existence of a pronounced hiatus in sedimentation between sequences 1 and 2 in this area. This time gap could correspond to the deposition of the basal lacustrine succession

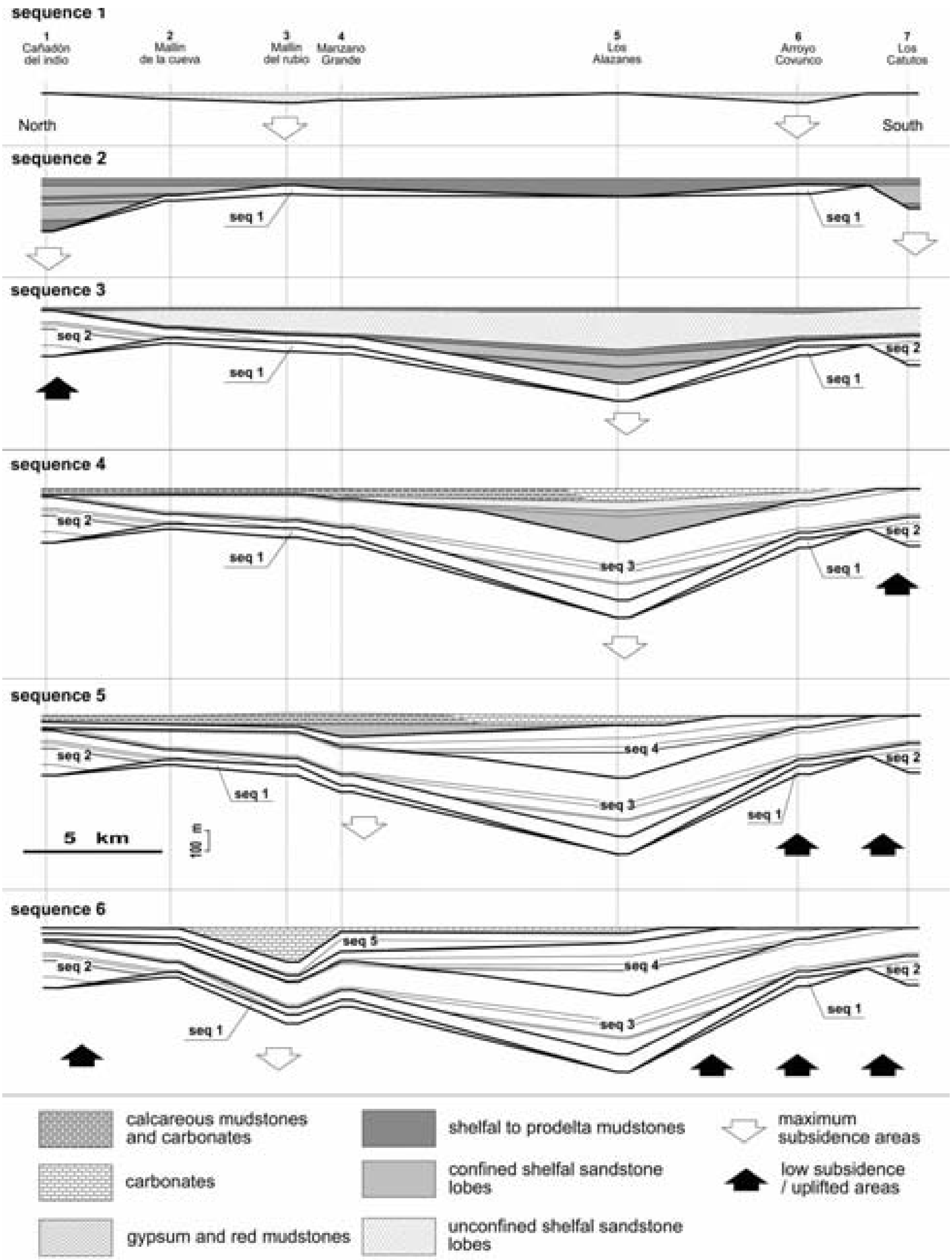

FIGURE 10 | **Diagram showing the progressive accumulation of the Lotena Group in the Sierra de la Vaca Muerta, with indication of the main facies types. White arrows for each sequence show the location of areas of low topographic relief, attributed to greater subsidence rates at time of deposition, while black arrows indicate the location of areas experienced less subsidence or uplift. Note the progressive northward shift of sequences 4 to 6 depocentres. Numbers on top refer to stratigraphic sections (see Fig. 2 for location).**

outcropped in the Loncopué area (Fig. 1). These levels are located at the base of the Lotena Formation between the Tábanos Formation and the overlying marine levels (Zavala et al., 2002). This early lacustrine succession was not recognized in the Sierra de la Vaca Muerta, and may be partially equivalent of the residual conglomerates described at the base of sequence 2, with paleocurrents azimuths towards the northwest in section 1.

The location of the topographic lows, which coincide with the areas of maximum subsidence during deposition for sequences 2 to 5, show a progressive migration towards the north (Fig. 10). This northward shift probably coincides with uplift and erosional truncation in southern areas, especially during the deposition of sequences 5 and 6. This erosional truncation resulted in the total absence of carbonate facies in section 7 at Los Catutos, where the conglomerates of the Tordillo Formation onlap directly over clastic deposits of sequence 3 (Figs. 3 and 10). This truncation is attributed to the progressive uplift of the Covunco anticline (Fig. 4). In particular, the uplift of this structure also controlled the thickness of the succeeding Tordillo Formation as this unit shows a maximum thickness of 60 m above the anticline, while at Manzano Guacho, 9.3 km to the north, this unit is 278 m thick.

CONCLUSIONS

Field studies in the Sierra de la Vaca Muerta and Covunco areas (southwestern Neuquén Basin) show that the Lotena Group consists of six unconformity-bounded units or sequences.

The first sequence is composed of red beds and evaporites belonging to the Tábanos Formation, and unconformably overlies strata of the Cuyo Group with a transgressive onlap.

Sequences 2 to 5 display a sandstone basal interval of confined shelfal sandstone lobes, which grade vertically into unconfined shelfal sandstone lobes, and end with carbonate deposits. The basal interval is restricted to areas where these sequences are thickest.

Sequence 6 has an irregular shape and markedly truncates the previous deposits. It is almost entirely composed of massive carbonate strata that were deposited by density currents. Both facies analysis and stratigraphic mapping suggest the existence of some reworking and redeposition from previous accumulations.

Stratigraphic evidence suggests that the Lotena Group in the Sierra de la Vaca Muerta and adjacent areas probably accumulated over a tectonically unstable substrate. Sequences 4, 5 and 6 show a northward shift of their depocentres and widespread truncation along the southern margin. This truncation could be related to intermittent uplift episodes associated with the synsedimentary growing of the Covunco anticline.

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