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Emplacement of Jurassic-Lower Cretaceous radiolarites of the Nicoya Complex (Costa Rica)

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ABSTRACT

We present a new model to explain the origin, emplacement and stratigraphy of the Nicoya Complex in the NW part of the Nicoya Peninsula (Costa Rica) based on twenty-five years of field work, accompanied with the evolution of geochemical, vulcanological, petrological, sedimentological and paleontological paradigms. The igneous-sedimentary relation, together with radiolarian biochronology of the NW-Nicoya Peninsula is re-examined. We interpret the Nicoya Complex as a cross-section of a fragment of the Late Cretaceous Caribbean Plateau, in which the deepest levels are exposed in the NW-Nicoya Peninsula. Over 50% of the igneous rocks are intrusive (gabbros and in less proportion plagiogranites) which have a single mantle source; the remainder are basalts with a similar geochemical signature. Ar^{39}/Ar^{40} radioisotopic whole rock and plagioclase ages range throughout the area from 84 to 83 Ma (Santonian) for the intrusives, and from 139 to 88 Ma (Berriasian-Turonian) for the basalts. In contrast, Mn-radiolarites that crop out in the area are older in age, Bajocian (Middle Jurassic) to Albian (middle Cretaceous). These Mn-radiolaritic blocks are set in a "matrix" of multiple gabbros and diabases intrusions. Chilled margins of magmatites, and hydrothermal baking and leaching of the radiolarites confirm the Ar^{39}/Ar^{40} dating of igneous rocks being consistently younger than most of the radiolarian cherts. No Jurassic magmatic basement has been identified on the Nicoya Peninsula. We interpret the Jurassic-Cretaceous chert sediment pile to have been disrupted and detached from its original basement by multiple magmatic events that occurred during the formation of the Caribbean Plateau. Coniacian-Santonian (Late Cretaceous), Fe-rich radiolarites are largely synchronous and associated with late phases of the Plateau.

KEYWORDS **Nicoya Complex. Jurassic-Cretaceous. Radiolarites. Cherts. Caribbean Plateau. Basalts. Gabbros. Pacific margin. Costa Rica.**

INTRODUCTION

The Nicoya Complex was formally described by Dengo (1962a; 1962b); since then, this unit has been studied by many authors with very different points of view. Most of these studies were made in the Nicoya Peninsula (Fig. 1), but the nomenclature of Nicoya Complex was also extended to other Costa Rican occurrences of oceanic assemblages, despite of their different ages and origin. We use the nomenclature of Nicoya Complex following the next definition: The Nicoya Complex, a basaltic sequence older than Lower Campanian-Santonian (>74 Ma), mainly composed of olivine tholeiites that occur as massive and pillow flows, dikes, and hyaloclastic pillow breccias. Subordinate igneous rocks include alkali-olivine basalts, gabbros, diabases and plagiogranites, including granophyres with hedenbergite and ferrodiabases with fayalite (Tournon, 1984). Deep-sea radiolarian cherts were deposited from the Middle Jurassic to the Late Cretaceous (Baumgartner, 1984a), but their contact with the volcanic rocks is almost always associated with intrusions of diabases and gabbros, and also it is disturbed by tectonics.

This paper focuses on the Nicoya Complex occurrences in the Nicoya Peninsula (Fig. 2). We present a model which integrates the nowadays known Ar^{39}/Ar^{40} radioisotopic dating, together with the radiolarian biochronologic ages, in order to understand the regional significance and the relationships between igneous and sedimentary rocks.

GEOLOGIC SETTING

The Middle American Trench presently separates the Cocos and Caribbean plates, and the Panama Fracture Zone delimits the Cocos from the Nazca plates (Fig. 1). Convergence rates of nearly 10 cm/year have been measured across the Costa Rican segment of the Middle American Trench (DeMets et al., 1990). Costa Rica belongs to the Caribbean Plate and it constitutes its western edge in southern Central America. The Cocos Plate formed 26 Ma ago, from the break-up of the Farallon Plate when the Cocos-Nazca spreading centre opened (Hey, 1977). The boundary between crust that originated in Pacific and Cocos-Nazca spreading centres was assumed by Hey (1977) to be offshore the Nicoya Peninsula, but this interpretation is questioned by Barckhausen et al. (1998). The subduction of Cocos Plate underneath the Caribbean Plate is hampered by the aseismic Cocos Ridge which attempts to subduct beneath southern Costa Rica (Fig. 1). The Cocos Ridge was generated from the Galapagos Hotspot. Its collision against the Caribbean Plate has caused the uplift of the Talamanca and the Fila Consteña mountain ranges and the extinction of volcanism during the last 5 Ma (Gräfe, 1998). Today, subduction of seafloor roughness generates tectonic erosion and subsidence of the offshore margin wedge. According to Ranero and von Huene (2000), and von Huene et al. (1995) the tectonic erosion recognized in relation to the Cocos Ridge collision in southern Costa Rica, could also be extended along much of the Middle America convergent margin. However, the long term geologic record indicates a mass balance of accretion rather than erosion.

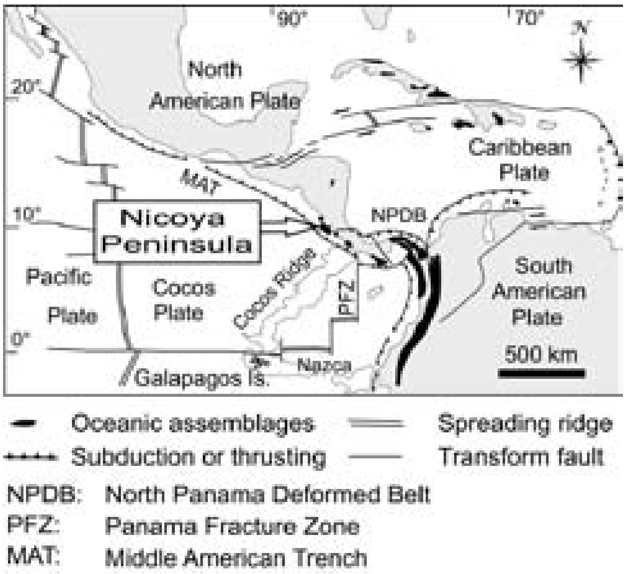


FIGURE 1 | **Present day plate tectonic setting of Central America and the Caribbean.**

Extensive outcrops of oceanic affinity assemblages occur along the southern Central America Pacific coast and they are somehow related to the active Cocos-Caribbean margin. One of the fundamental controversies is where most of these oceanic suites were formed, and this problem is directly related to the regional modelling involving the formation of the Caribbean Plate. Malfait and Dinkelmann (1972), Donnelly (1973), Donnelly et al. (1973), and later Burke et al. (1978) hypothesized that large parts of the present Caribbean Plate were formed in the Pacific as anomalously thick, buoyant crust that then became displaced between the Americas. Duncan and Hargraves (1984) hypothesized that the Galapagos mantle plume was responsible for the thickened Caribbean crust. The Nicoya Complex was then regarded by several authors (Galli-Olivier, 1979; Kuijpers, 1980) as an example of Caribbean Crust composed of Jurassic MORB magmatics, overlain by oceanic sediments, which are in turn overlain by magmatic rocks attributed to the Caribbean Plateau.

In opposition to the above models of a general allocthony of the Caribbean, Frisch et al. (1992) and Meschede and Frisch (1998) proposed a fixist model of formation of the Caribbean Plateau by the separation of North and South America, and they concluded that the Nicoya Peninsula genetically belongs to the Caribbean plate. In contrast, Di Marco et al. (1995) included the Nicoya Peninsula into the Nicoya Terrane that was about 16° of south latitude in Late Cretaceous times.

Geochemical data and Ar^{39}/Ar^{40} dating by Sinton et al. (1997), Alvarado et al. (1997), Hauff et al. (1997), Hauff et

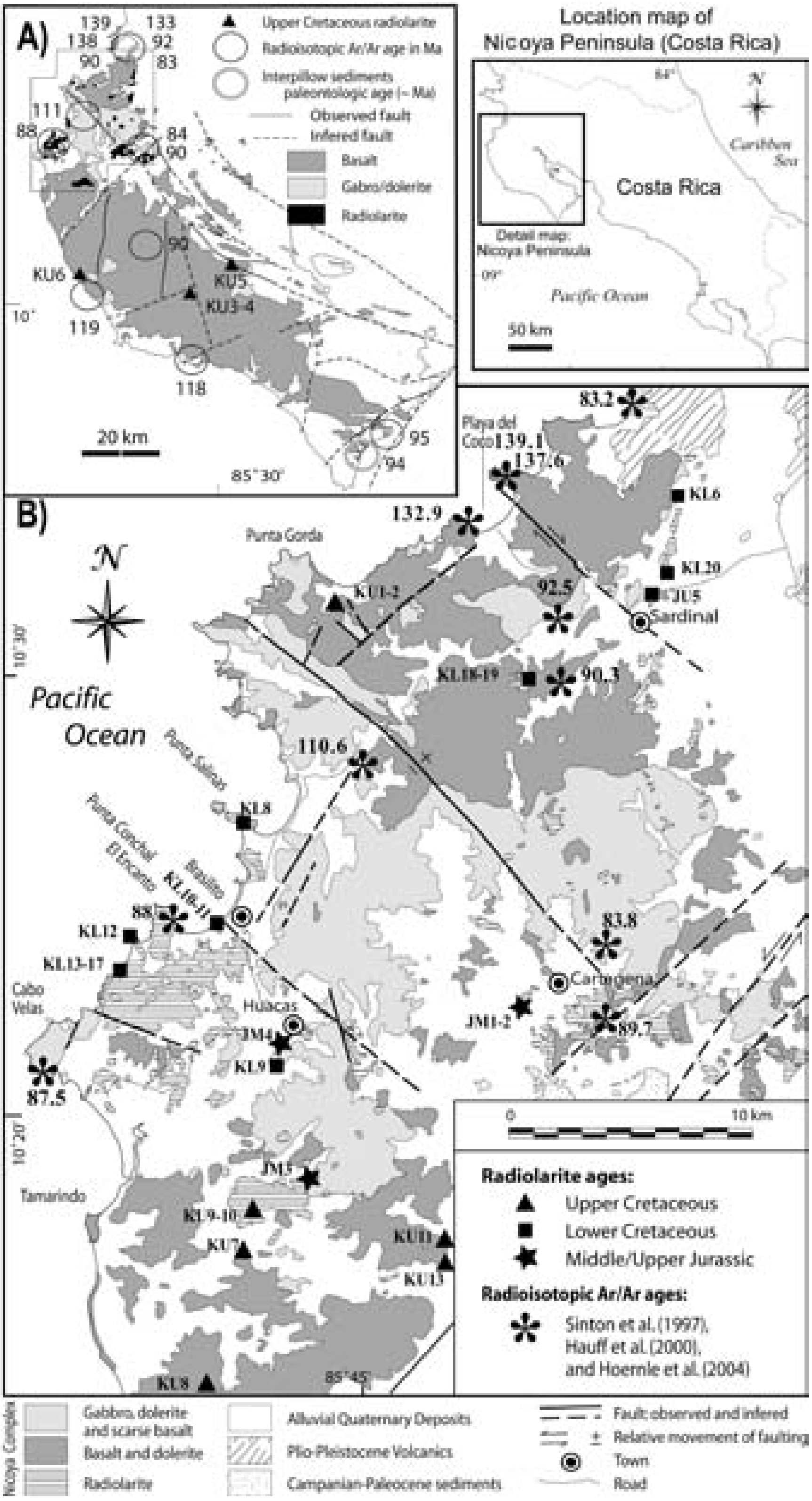


FIGURE 2 **A) Simplified Geologic map of the Nicoya Peninsula, with the location of the study area and other localities cited in the text. Based on Dengo (1962a), and unpublished data. B) Geologic map of the NW-Nicoya Peninsula after Denyer and Arias (1993), sample location of Middle Jurassic to Late Cretaceous radiolarian assemblages, and localities of Ar^{39}/Ar^{40} radioisotopic ages.**

al. (2000) and Hoernle et al. (2004) have largely confirmed the view of the Nicoya Peninsula as a portion of the Caribbean Plateau or a geochemically similar plateau of the Eastern Pacific. The Late Cretaceous Ar^{39}/Ar^{40} data are in contradiction to previous radiolarian biochronology of the northern Nicoya Peninsula (Baumgartner, 1984a, 1987; Baumgartner et al. 1995) that yield Middle Jurassic to Late Cretaceous ages.

PREVIOUS WORK

The Nicoya peninsula is dominated by the Nicoya Complex, which was defined by Dengo (1962a) as a Cretaceous assemblage of different rocks with intricate stratigraphic and structural relations deserving the term complex. The lithologies included were igneous and sedimentary, specifically cherts, siliceous limestones, basalts, basalt-agglomerates, diabases, gabbros and diorites. Kuijpers (1980) redefined the Nicoya Complex preserving the oceanic assemblage (basalts, gabbros, diabases and radiolarites), and excluding the sedimentary cover.

One of the first hypotheses of emplacement of the oceanic suite of the Nicoya Complex was proposed by Galli-Ollivier (1979). He suggested mélange formation in an accretionary prism to explain the outcrops of the NW Nicoya peninsula. In contrast, Schmidt-Effing (1979, 1980a, 1980b) subdivided the Nicoya Complex into subcomplexes (Fig. 3), based on the nature and age of “xeno-

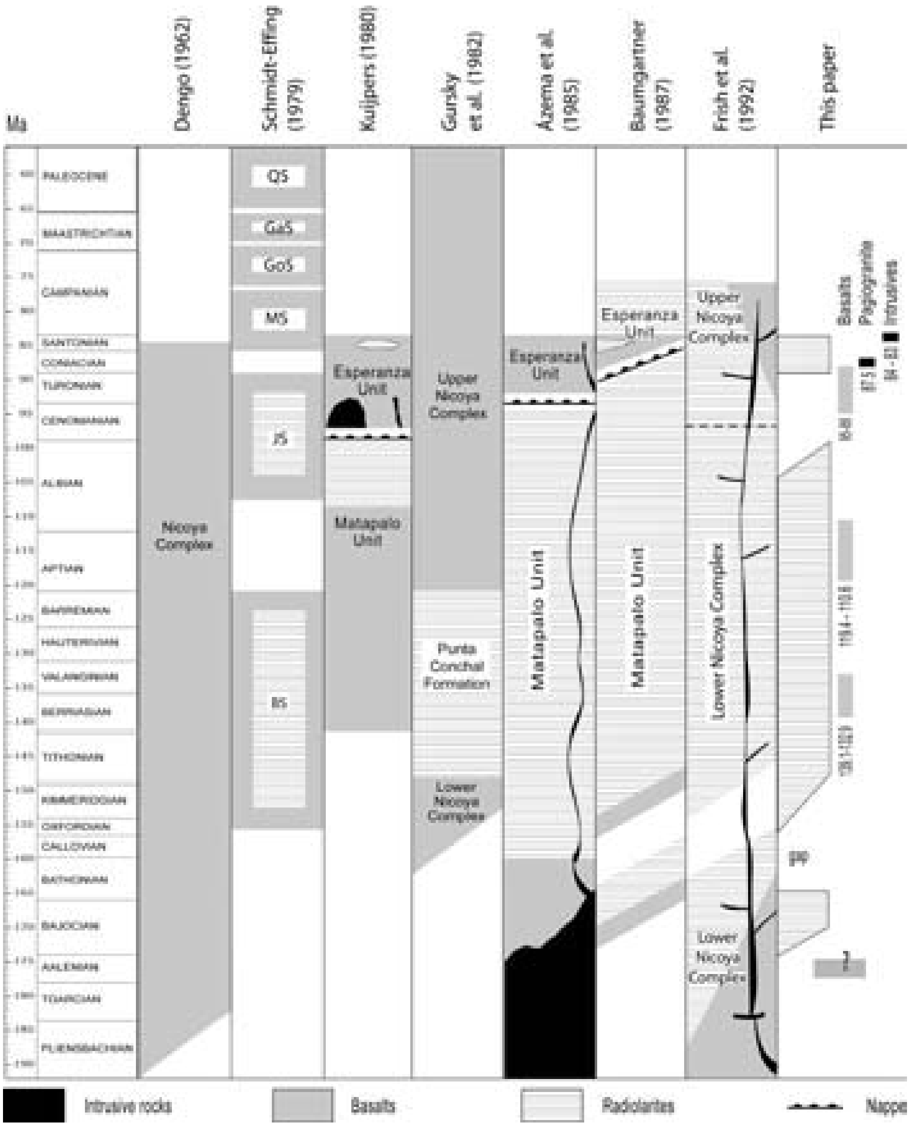


FIGURE 3 | **Compared stratigraphic columns of the Nicoya Complex by different authors. BS: Brasilito Subcomplex; JS: Junquillal Subcomplex; MS: Murcielago Subcomplex; Go: Golfito Subcomplex; Ga: Garza Subcomplex; QS: Quepos Subcomplex. Time scale based on Channell et al., 1995; Gradstein et al., 1995, and Palfy et al., 2000.**

liths" of sedimentary rocks included in the basalts. He extended the term "Nicoya Complex" to other oceanic assemblages cropping out in central and southern Pacific of Costa Rica, despite the differences in igneous and sedimentary stratigraphy and age.

Kuijpers (1980) interpreted the Nicoya Complex of the north-western Nicoya Peninsula, as an obducted nappe edifice formed during the beginning of subduction along the Middle American convergent margin. He mapped two informal units: Matapalo and Esperanza (Fig. 3), based on detailed lithologic observations and preliminary radiolarian dating from P.O. Baumgarnter, which were formally published four years later (Baumgartner, 1984a). Kuijpers (1980) interpreted Matapalo as the older unit, overthrusted by the younger Esperanza unit. Azéma et al. (1984) agreed on the nappe structure, but believed the older unit (Matapalo) overthrusted the younger Esperanza unit. Baumgartner et al. (1984) and Burgois et al. (1984) divided the geologic history of this region into two episodes: (1) A pre-Campanian episode during which the nappe edifice, comprising the Santa Elena and Matapalo nappes, formed; and (2) A post early Campanian phase of sedimentation on the stabilized, subsiding relief created by the first episode. Azéma et al. (1985) (Fig. 3) followed the Kuipers stratigraphy, but, as well as Frisch et al. (1992), considered the Matapalo nappe as a Matapalo overthrust, placing the Matapalo unit above the younger Esperanza unit.

Baumgarnter (1984a, 1984b, 1987) using the Kuijpers (1980) stratigraphy, interpreted the biostratigraphic history based on radiolarian dates (Fig. 3). Frisch et al. (1992) composed a stratigraphic column (Fig. 3) using data from Schmidt-Effing (1979), Tournon (1984) and Baumgartner (1987). They combined the Gursky et al.'s (1982) stratigraphy with Baumgarnter's biostratigraphy.

In relation to petrology, Wildberg (1984) did the first systematic analysis of igneous geochemistry on the Nicoya Peninsula. He concluded that both MORB and primitive island arc rocks are present in the peninsula. Gursky (1984) mapped all shorelines of the Peninsula. Gursky et al. (1982, 1984) designed a threefold stratigraphy of the Nicoya Complex: first, the Lower Nicoya Complex, which was interpreted as Jurassic oceanic basement, stratigraphically overlain by a second unit, the Punta Conchal Formation, a Late Jurassic-Early Cretaceous radiolarite sequence, which is in turn conformably overlain by the oceanic basalts of the third unit, the Upper Nicoya Complex. This view of the Nicoya Complex has been largely accepted in the literature, despite the fact that no stratigraphic contacts have been documented and that the radiolarite sequences are highly disrupted and stratigraphically incoherent (Baumgartner, 1984a, 1984b, 1987). Meschede and Frisch (1994) published one of the major bases of geochemical analyses from various basaltic units along the Costa Rican Pacific coast. They found mid-ocean ridge basalts, island arc tholeiites, within-plate tholeiites and alkali basalts.

The modern analyses began with Hauff et al. (1997) and Sinton et al. (1997) who basically worked in the Nicoya peninsula. Sinton et al. (1997) also did the first group Ar^{39}/Ar^{40} radioisotopic dates of the Nicoya peninsula. Beccaluva et al. (1999) did more than 30 analyses in Santa Elena peninsula, and Matapalo and Esperanza units in the Nicoya peninsula. These analyses included major, trace elements and Rare Earth Elements (REE). Hauff et al. (2000) analyzed all the oceanic assemblages of Costa Rica, including the Nicoya Peninsula, with additional Ar^{39}/Ar^{40} dating. Hoernle et al. (2002) included geochemical and Ar^{39}/Ar^{40} radioisotopic ages of the unknown rocks of Azuero and Soná peninsulas and Coiba Island. Finally, Hoernle et al. (2004) found some radioisotopic ages in the Nicoya peninsula, which are older than the Caribbean Large Igneous Province (CLIP) age.

The authors after Frisch et al. (1992) did not put their new data in a stratigraphic context (Fig. 3). Hauff et al. (1997) presented a general column with thrusting between the 90 Ma volcanic series, radiolarites thrust over the volcanics and the intrusives under them. The very detailed geochemical study of Hauff et al. (2000) included some stratigraphic columns, but the authors focused on the geochemical data and its petrological and geotectonic significance. The apparent inconsistencies between the Ar^{39}/Ar^{40} ages and radiolarian dates were recognized by Hauff et al. (1997) and Sinton et al. (1997), but no explanation was given. Both groups of authors concluded that the radiolarites ages do not necessarily represent the formation age of the igneous neighbour rocks.

IGNEOUS SUITE

Tholeiitic basalts occur along the entire Nicoya Peninsula; gabbros and plagiogranites together with the major outcrops of radiolarites are concentrated in its northwest (Fig. 2). In the area between Tamarindo and Sardinal (Fig. 2), over 50% of the igneous rocks are intrusive, such as holocrystalline gabbros and plagiogranites that have a single source, common with the basalts.

The basalts are fine grained, generally aphyric, consisting of plagioclase, augite, chlorite and Fe-Ti oxides set in an altered aphanitic matrix. In the field, massive basalt flows dominate, they are crossed by several generations of fractures and xeolithic and siliceous veins. Well-preserved pillow structures are rare in the N-Nicoya Peninsula, but common in the southwest and south of Nicoya.

Diabases (cm and m wide) cut both, magmatic and radiolaritic sequences. They have the same mineralogical assemblage, but can be recognized in the field, because they cross-cut massive basalts, and may show holocrystalline texture and trace amounts of tabular apatite. Some characteristic dikes containing rounded centimeter-long anorthite megacrystals (An_{88-83}, Tournon, 1984) cut the massive basaltic sequences.

Gabbros and micro-gabbros belong to the Potrero Intrusive unit (Denyer and Arias, 1983). The main body crops out in an area up to 200 km^2. Gabbros have the same mineralogy as diabases and basalts but have larger grain sizes, up to 1 cm. The plagiogranites have coarse textures, with grain sizes up to 2 cm. Mineralogically, they contain myrmekitic plagioclase, quartz, hedenbergite, and Fe-Ti oxides (Sinton et al., 1997; Denyer and Arias, 1993).

Ar^{39}/Ar^{40} radioisotopic summary

Thirteen Ar^{39}/Ar^{40} dates (whole rock, glass and plagioclase) have been done in the study area (Fig. 2). The data show a wide range of ages. Dates of 84-83 Ma (Santonian) were obtained for the intrusives. The basalts yield dates of 95-88 Ma (Cenomanian-Turonian) (Sinton et al., 1997; Hauff et al., 2000), 139-133 Ma (Berriasian-Hauterivian) and 119-111 Ma (Aptian-Albian) (Hoernle et al., 2004).

From the petrological data available, the prior designation of clear magmatic units (Schmidt-Effing, 1979; Kuijpers, 1980; Burgois et al., 1984; Gursky et al., 1984; Wildberg, 1984; Frisch et al., 1992) in the Nicoya Complex is untenable. The petrological and Ar^{39}/Ar^{40} similarities in the data from Sinton et al. (1997) and Hauff et al. (2000) make a clear argument to relate the 95-83 Ma (95-88 Ma of intrusives, 87.5 Ma of plagiogranite and 95-88 Ma of basalts) magmatic suite genetically to the Caribbean Plateau. More specifically, the Nicoya Complex could represent disrupted fragments of the CLIP. More recently, Hoernle et al. (2004) found older ages in basalts (139-69 Ma) that they consider petrologically belonging to the CLIP, but interpret them as remnants of the earlier history of the Galapagos hotspot. Part of these magmatics, basically the 139-133 Ma basalts, could be the basement of part of the radiolarites (Fig. 3). The 119-111 Ma basaltic suite must be, at least in part, responsible for the manganese mineralizations, as we shall explain later.

RADIOLARITES

The only sedimentary rocks that are included here within the Nicoya Complex are intensely deformed, ribbon-bedded radiolarian cherts (Figs. 2 and 3) and associated hydrothermally produced jasper and ore deposits (Kuijpers, 1980). Other sedimentary lithologies, such as siliceous mudstones, pelagic limestones and turbidites belong to the unconformably overlying rock series, the Sabana Grande, Loma Chumico, Berrugate, Puerto Carrillo and Curú formations. Radiolarian-rich outcrops are concentrated in the NW Nicoya Peninsula (Fig. 2).

The radiolarian biochronology of the study area (Fig. 4A) has been done using the biozonations of O'Dogherty (1994) and Baumgartner et al. (1995) for the Middle Jurassic to middle Cretaceous radiolarian occurrences. Middle and Late Jurassic samples were compiled using the biochronology of Baumgartner et al. (1995), using the UAZ95 zonation. Additional information was derived from the zonation of Sanfilippo and Riedel (1985) for species that are not represented in the former zonations. To obtain the age range of the Late Cretaceous samples we used the zonations by Foreman (1975), Pessagno (1976), Taketani (1982), Sanfilippo and Riedel (1985) and O'Dogherty (1994).

Based on the lithology and ages, two facies can be distinguished in the Nicoya Complex: Mn-radiolarites and Fe-radiolarites (Kuijpers, 1980).

Mn-radiolarites

They are Jurassic to middle Cretaceous in age (Baumgartner, 1984a) and form the largest outcrops between Cabo Velas, El Encanto, Punta Salinas Cartagena and Sardinal (Fig. 2). Major Mn-mineralizations and massive, red hydrothermal jasper bodies are associated with this type of radiolarites. These form 5 m thick and 100 m long lenses, probably related to hydrothermal activity (Kuijpers and Denyer, 1979). Individual rock bodies are up to 40 m thick, show cm-ribbon bedding (Fig. 5A) of brown, red, greenish, white or gray or black chert with usually darker colored shale partings. Radiolarites show very intense folding and faulting; chevron and isoclinal folds are common. Tectonic thickening due to superimposed folding, gives the impression of a much thicker rock sequence (Kuijpers, 1980). In some localities manganese nodules (Fig. 5B) of a probable sedimentary origin occur (Halbach et al., 1992). While previous authors (Kuijpers and Denyer, 1979; Addy and Kuijpers, 1982) considered a hydrothermal genesis, Hallbach et al. (1992) postulated a primary sedimentary origin of the fossil manganese nodules, which were later hydrothermally remobilized, changing the original todokorite into braunite. The Mn-radiolarites formed in the equatorial Pacific Ocean under oxygenated bottom waters (Gursky, 1984) and presumably with very low sedimentation rates.

Biochronology

Several Middle Jurassic radiolarian assemblages (Figs. 6 and 7) were recovered from inland outcrops of heavily deformed ribbon-bedded NW-bearing radiolarites. In Baumgartner (1984a, 1987) assigned these faunas to a Bathonian-Callovian age by using Baumgartner (1984b) zonation. More recent revisions of the ammonite biochronology that served as calibration for the radiolarian zones (Baumgartner et al., 1995) resulted in an older calibration of the same radiolarian assemblages. The oldest assemblages of the NW-Nicoya Peninsula now correlate with UAZ 4-5 (Bajocian) and are illustrated (Figs. 4 and 7).

No late Middle or early Late Jurassic assemblages could be identified in the Nicoya Complex. This suggests

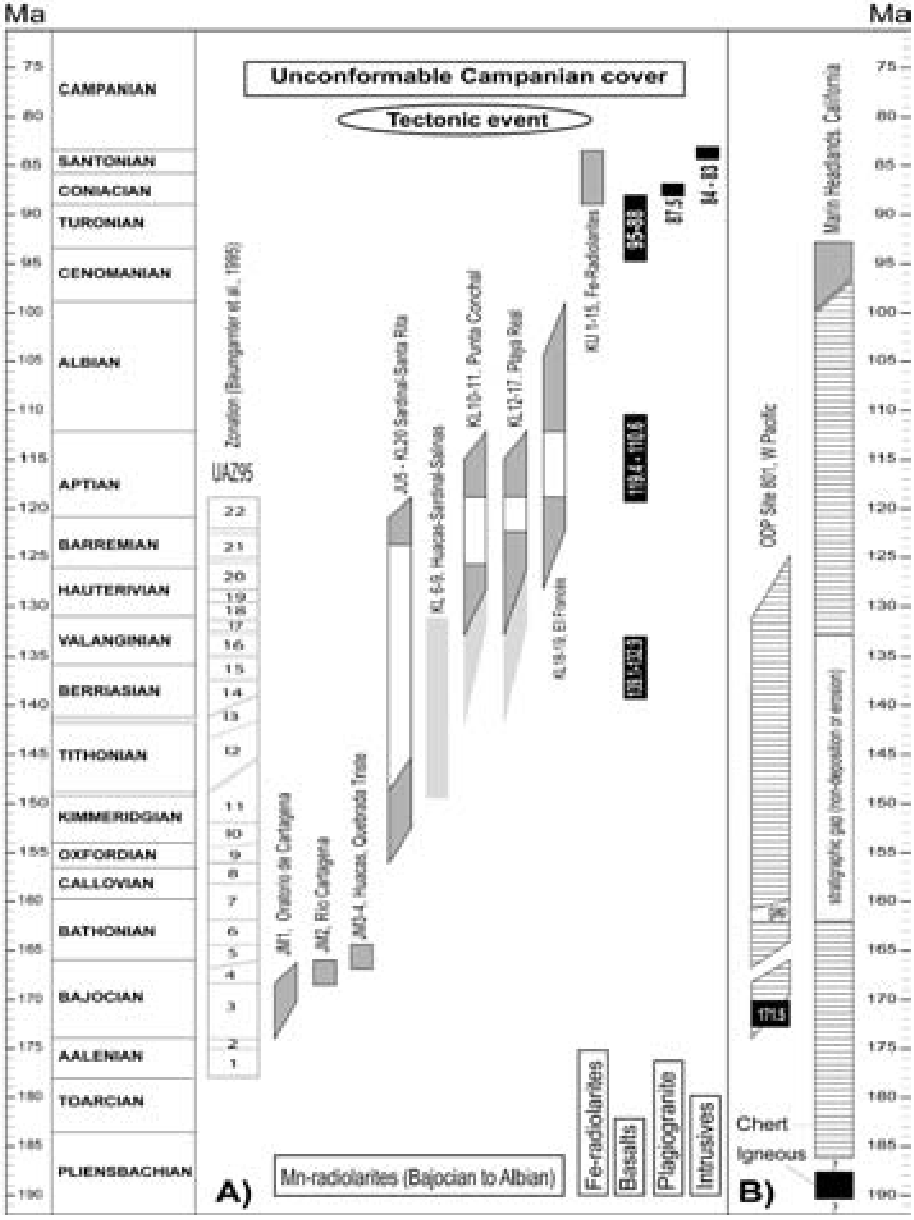


FIGURE 4 | **A) Synthesis of bio- and geochronologic ages determined in MW-Nicoya. Fields shaded in grey represent biochronologic age ranges of radiolarian samples, from selected localities (Fig. 2). Oblique upper and lower ends of fields indicate age uncertainties. Connected fields (e.g. Punta Conchal) indicate stratigraphic columns with ages of the lowest and the highest sample indicated, lightly shaded fields indicate poorly defined ages, due to poor preservation. Igneous in black, the numbers are Ar^{39}/Ar^{40} ages (Sinton et al., 1997; Hauff et al., 2000 and Hoernle et al., 2004). Time scale as in Fig. 3. B) Siliceous sediment sequences of ODP Site 801, in the western Pacific (Bartolini and Larson, 2001), and the Geysers chert, Marin Headlands Terrane (after Murchey, 1984).**

the presence of a stratigraphic gap spanning at least the middle Bathonian-Early Oxfordian interval (Fig. 4A). The only clearly Late Jurassic assemblages in this data set were recovered north of Sardinal (Fig. 2). Schmidt-Effing (1980b) cites *Eucyrtidiellum ptyctum* from the Playa Real-Punta Conchal area. This could indicate latest Juras-

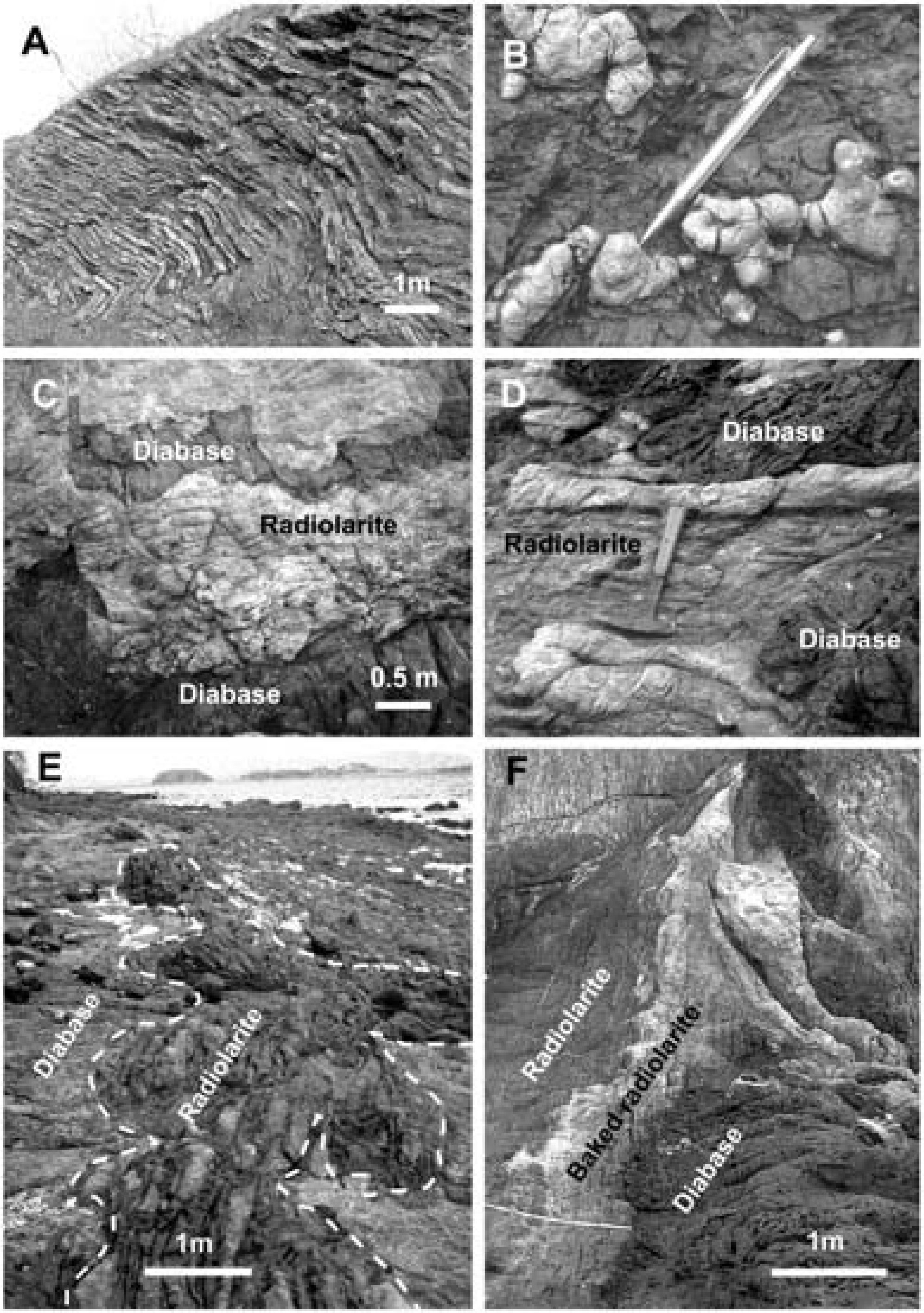


FIGURE 5 | **Mn-radiolarites and their magmatic-tectonic contacts. A) Ribbon-bedded Mn-radiolarites with pervasive open chevron folding. This photograph was taken along road Huacas-Playa Brasilito (Fig. 2). Bed thickness 5-10 cm. B) Mn-nodules in radiolarites The nodules were digitally enhanced, in order to distinguish in greyscale. Locality SW El Encanto (Fig. 2). The pen is 12cm long. C) Sill above main diabase intrusion in leached radiolarie, Punta Salinas. Sill intruded along pre-existing faults and is later faulted itself. D) Pervasive contact between diabase and light coloured (bleached) radiolarites at Punta Gorda (Fig. 2). E) Radiolarite layer enclosed in coarse grained, rather leucocrate diabases. Diabase partially destroyed radiolarian chert and penetrated along faults and bedding planes. Beds in forefront 10-20 cm thick. This photograph was taken in El Encanto (Fig. 2). F) Diabase-radiolarite contact at Punta Gorda (Fig. 2). About 1 m of radiolarite is baked and leached.**

sic maximum ages at these localities, whereas our data contain only early Cretaceous radiolarians.

By far most localities yield early Cretaceous assemblages that range in age from Late Valanginian (determined by the presence of *Cecrops septemporatus*) to Aptian (Figs. 4A and 6). Several mid-Cretaceous assemblages (Fig. 6) are dominated by *Pantanellium* spp. The dominance of this group can even be recognized in thin section (Fig. 8). We interpret this monophyletic abundance as blooms of opportunistic species in an equatorial upwelling zone. A similar setting has been suggested for the related pantanelliid group *Valupinae* by Matsuoka (1995). The Albian is indicated by the presence of *Pseudodictyounitra pseudomacrocephala* and other characteristic species (Fig 6 and 7).

Fe-radiolarites

These Late Cretaceous (Coniacian-Santonian) radiolarites form 3-10 m thick sequences that overlie the igneous assemblage or are intercalated as lenses in the basalts. Whitish/brown or red cm-thick ribbon bedding characterizes this unit. Parts of this unit are impregnated with hematite, by a pervasive cross cutting of hematite veinlets. Locally, original cherts are completely transformed into hematitic rock. Hematitic veins also cross-cut the basalts, which underlie hematitic radiolarites, and sometimes they show an intense pyritization (Kuijpers, 1980).

Biochronology

Small outcrops of limonite-hematite-bearing bright red-orange thin-bedded chert are wide spread in the southern part of the studied area. This suggests a high position in or on top of the mid Cretaceous plateau. The radiolarian assemblages of these outcrops are very homogeneous and contain all very similar assemblages (Figs. 6 and 7), which can be tentatively assigned to a Coniacian-Santonian age. Biostratigraphically important species are: *Alievium praegallowayi* Pessagno (Coniacian -Early Santonian), *Dictyomitra formosa* (Squinabol) (Coniacian-Santonian), *Pseudictyomitra nakasekoi* Taketani (Turonian-Coniacian), *Praeconocaryomma universa* Pessagno (Coniacian-Campanian) and *Theocampe urna* Foreman (Late Coniacian-Late Campanian), *Pseudoaulophacus lenticulatus* White *(*Coniancian-Late Campanian).

Related radiolarite occurrences

The comparison of this restored radiolarite sequence of NW-Nicoya with siliceous sediment sequences of western Pacific (ODP Site 801) and Marin Headlands (California) shows similar stratigraphic gaps during the late Middle and Late Jurassic (Fig. 4). These gaps vary, however, in duration with each site. On the other hand the Middle Jurassic assemblages of Nicoya compare rather well with North American assemblages from the Marin Headlands, the Yolla Bolly or other Fransiscan terranes, rather than with Tethyan assemblages. *Ristola turpicula* Pessagno is a typical "Pacific" species in these assemblages.

A radiolarian assemblage similar to our Fe-radiolarite associations was described by Meyerhoff-Hull and Pessagno (Kolarsky et al., 1995) from the west coast of the Azuero Peninsula, Panamá.

SEDIMENTARY-IGNEOUS RELATIONSHIPS

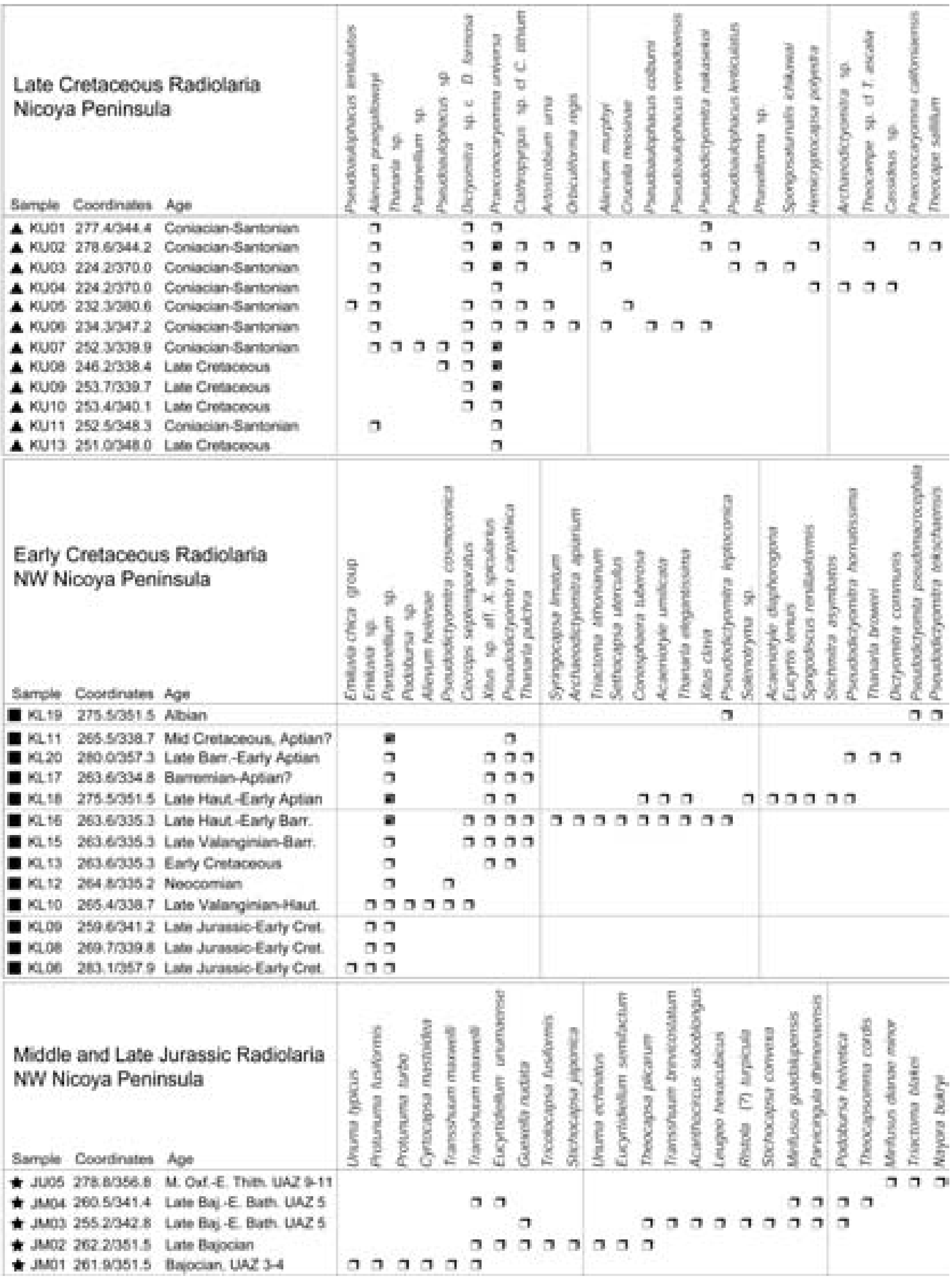
Kuijpers (1980) believed that all contacts between radiolarites and igneous rocks were tectonically controlled. Schmith-Effing (1979), observed the existence of magmatic contacts, and interpreted the radiolarites as xenoliths in basalts. Azéma et al. (1984) believed that most of the contacts were tectonic, but they also recognized magmatic relationships between radiolarites of Matapalo unit and two different diabases in the Huacas section. Gursky and Gursky (1988) remarked on the presence of magmatic contacts between the radiolarites and the basaltic-doleritic and gabbroic series.

Most descriptions of the Nicoya Complex were based on observations made in the excellent outcrops along the shoreline and along new inland roads. Denyer and Arias (1993) published the first detailed geologic map (1:50,000) for this area (Fig. 2), which is the basis of our interpretation. Large kilometer bodies of intrusive rocks are exposed inland and they are spatially related to the radiolarites of Jurassic to Lower Cretaceous age. Because of a general absence of pillow structures, it is difficult to establish structural trends in the basaltic units. It is, therefore, impossible to establish which basalt is structurally below or above a radiolarite body. Moreover, the re-examination of contacts between basalts, gabbros and radiolarian chert shows hot, intrusive contacts in all localities and on all sides of the radiolarite bodies. This clearly means that the radiolarites are stratigraphically incoherent blocks of sediment set in a "matrix" of multiple diabasic intrusions, and posterior crosscutting dikes and sills (Figs. 5C to 5F).

The relationship between magmatic and radiolaritic rocks can be well observed in outcrops at Punta Gorda (Figs. 5D and 5F), El Encanto (Fig. 5E), just in the cliff where a sample yielding a 88 Ma Ar^{39}/Ar^{40} radioisotopic age was taken, and also, at La Marina near the hotels of Flamingo (Southern cliff of Potrero beach), and at Punta

Salinas, (Fig. 5C). In the contact zones, the bedded cherts are partially reabsorbed, metamorphosed and/or hydrothermally bleached. Basalts and diabases show chilled margins in contact with the sediment. Intense hydrothermal leaching of the Mn-bearing radiolarites resulted in Mn-mineralization and jasper bodies that are concentrated along the magmatic/sediment contacts.

All radiolarite bodies are affected by a pervasive, soft sediment deformation, which causes difficulties for the



Late Cretaceous Radiolaria
Nicoya Peninsula

Sample	Coordinates	Age	Pseudoaulophacus ambulatus	Alievum praegallowayi	Thanarla sp.	Pantanellium sp.	Pseudoaulophacus sp.	Dictyomitra sp. c. D. formosa	Praeconocaryomma universa	Clathropyrgus sp. cf C. tithium	Artostrobium urna	Orbiculiforma regis	Alievum murphyi	Crucella messinae	Pseudoaulophacus colburni	Pseudoaulophacus venadoensis	Pseudodictyomitra nakasekoi	Pseudoaulophacus lenticulatus	Phaseliforma sp.	Spongosaturnalis ichikawai	Hemicryptocapsa polyedra	Archaeodictyomitra sp.	Theocampe sp. cf T. ascalia	Cassideus sp.	Praeconocaryomma californiaensis	Theocape salillum
▲ KU01	277.4/344.4	Coniacian-Santonian		□				□	□								□									
▲ KU02	278.6/344.2	Coniacian-Santonian		□				□	■	□	□	□	□				□	□			□		□		□	□
▲ KU03	224.2/370.0	Coniacian-Santonian		□				□	■	□			□					□	□	□						
▲ KU04	224.2/370.0	Coniacian-Santonian		□					□												□	□	□	□		
▲ KU05	232.3/380.6	Coniacian-Santonian	□	□				□	□	□	□			□												
▲ KU06	234.3/347.2	Coniacian-Santonian		□				□	□	□	□	□	□		□	□	□									
▲ KU07	252.3/339.9	Coniacian-Santonian		□	□	□	□	□	■																	
▲ KU08	246.2/338.4	Late Cretaceous					□	□	■																	
▲ KU09	253.7/339.7	Late Cretaceous						□	■																	
▲ KU10	253.4/340.1	Late Cretaceous						□	□																	
▲ KU11	252.5/348.3	Coniacian-Santonian		□					□																	
▲ KU13	251.0/348.0	Late Cretaceous							□																	

Early Cretaceous Radiolaria
NW Nicoya Peninsula

Sample	Coordinates	Age	Emiluvia chica group	Emiluvia sp.	Pantanellium sp.	Podobursa sp.	Alievum helenae	Pseudodictyomitra cosmoconica	Cecrops septemporatus	Xitus sp. aff. X. spicularius	Pseudodictyomitra carpathica	Thanarla pulchra	Syringocapsa limatum	Archaeodictyomitra apiarium	Triactoma tithonianum	Sethocapsa uterculus	Conosphaera tuberosa	Acaeniotyle umbilicata	Thanarla elegantissima	Xitus clava	Pseudodictyomitra leptoconica	Solenotryma sp.	Acaeniotyle diaphorogona	Eucyrtis tenuis	Spongodiscus renillaeformis	Stichomitra asymbatos	Pseudodictyomitra hornatissima	Thanarla brouweri	Dictyomitra communis	Pseudodictyomitra pseudomacrocephala	Pseudodictyomitra lekschaensis
■ KL19	275.5/351.5	Albian																			□									□	□
■ KL11	265.5/338.7	Mid Cretaceous, Aptian?			■						□																				
■ KL20	280.0/357.3	Late Barr.-Early Aptian			□					□	□	□															□	□	□		
■ KL17	263.6/334.8	Barremian-Aptian?			□					□	□	□																			
■ KL18	275.5/351.5	Late Haut.-Early Aptian			■					□	□						□	□	□			□	□	□	□	□	□				
■ KL16	263.6/335.3	Late Haut.-Early Barr.			■				□	□	□	□	□	□	□	□	□	□	□	□	□										
■ KL15	263.6/335.3	Late Valanginian-Barr.			□				□	□	□	□																			
■ KL13	263.6/335.3	Early Cretaceous			□					□	□																				
■ KL12	264.8/335.2	Neocomian			□			□																							
■ KL10	265.4/338.7	Late Valanginian-Haut.		□	□	□	□	□	□																						
■ KL09	259.6/341.2	Late Jurassic-Early Cret.		□	□																										
■ KL08	269.7/339.8	Late Jurassic-Early Cret.		□	□																										
■ KL06	283.1/357.9	Late Jurassic-Early Cret.	□	□	□																										

Middle and Late Jurassic Radiolaria
NW Nicoya Peninsula

Sample	Coordinates	Age	Unuma typicus	Protunuma fusiformis	Protunuma turbo	Cyrtocapsa mastoidea	Transhsuum maxwelli	Transhsuum maxwelli	Eucyrtidiellum unumaense	Guexella nudata	Tricolocapsa fusiformis	Stichocapsa japonica	Unuma echinatus	Eucyrtidiellum semifactum	Theocapsa plicarum	Transhsuum brevicostatum	Acanthocircus suboblongus	Leugeo hexacubicus	Ristola (?) turpicula	Stichocapsa convexa	Mirifusus guadalupensis	Parvicingula dhimenaensis	Podobursa helvetica	Theocapsomma cordis	Mirifusus dianae minor	Triactoma blakei	Nayora bukryi
★ JU05	278.8/356.8	M. Oxf.-E. Tith. UAZ 9-11																							□	□	□
★ JM04	260.5/341.4	Late Baj.-E. Bath. UAZ 5						□	□												□	□	□	□			
★ JM03	255.2/342.8	Late Baj.-E. Bath. UAZ 5								□					□	□	□	□	□	□	□	□	□				
★ JM02	262.2/351.5	Late Bajocian						□	□	□	□	□	□	□	□												
★ JM01	261.9/351.5	Bajocian, UAZ 3-4	□	□	□	□	□	□																			

FIGURE 6 | **Radiolarian occurrences in Middle Jurassic to Early Cretaceous and Late Cretaceous chert samples form the-Nicoya Peninsula. The code in first column refers to localities shown in Fig. 2. Empty squares: present; full squares: very abundant.**

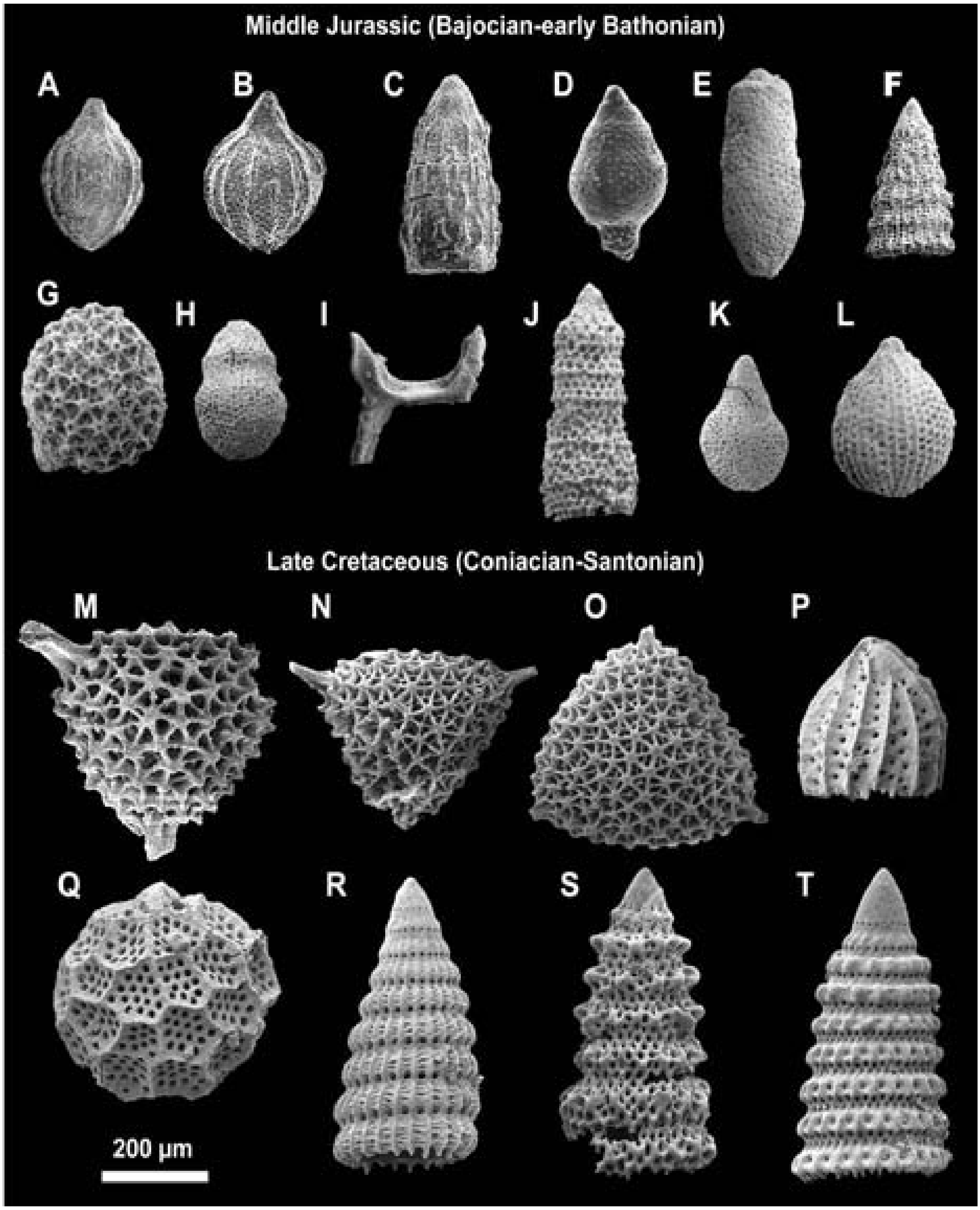


FIGURE 7 | **Radiolarians of the Nicoya Complex. A-L) Middle Jurassic (Bajocian-early Bathonian). A to D) Sample JM1 in front Oratorio de Cartagena. Age: UAZ95: 3-4, Bajocian. E to L) Sample JM3 (collected by E. Kuijpers in 1979). Age: UAZ95: 5, late Bajocian-early Bathonian. M to T) Late Cretaceous (Coniacian-Santonian) radiolarians from sample KU2, 4 km SE of Punta Gorda. A) *Protunuma turbo* MATSUOKA. Range: UAZ95: 4-7. B) *Protunuma fusiformis* YAO. C) T*ransshuum maxwelli* PESSAGNO group. Range: UAZ95: 5-6. D) *Cyrtocapsa mastoidea* YAO. Range: UAZ95: 3-4. E) *Guexella nudata* (KOCHER). Range: UAZ95: 5-8. F) *Transshuum brevicostatum* (OZVOLDOVA) group. Range: UAZ95: 3-11. G) *Leugeo hexacubicus* (BAUMGARTNER). Range: UAZ95: 4-8. H) *Theocapsomma* sp. I) *Acanthocircus suboblongus suboblongus* YAO. Range: UAZ95: 3-11. J) *Ristola* (?) *turpicula* PESSAGNO and WHALEN. Range: UAZ95: 5-6. K) *Stichocapsa convexa* YAO. Range: UAZ95: 1-11. L) *Tricolocapsa plicarum* MATSUOKA. Range: UAZ95: 4-5. M) *Alievium praegallowayi* PESSAGNO. Range: Coniacian-Early Santonian. N) *Alievium* sp. cf *A. gallowayi* (WHITE). This is transitional between *A. praegallowayi* and *A. gallowayi*. O) *Alievium murphyi* PESSAGNO. P) (?)*Rhopalosyringium* sp. Q) *Hemicryptocapsa polyedra* DUMITRICA. R) *Dictyomitra formosa* (SQUINABOL). S) *Crolanium* sp. aff. *C. pulchrum* SQUINABOL *sensu* O'Dogherty (1994). T) *Pseudodictyomitra nakasekoi* TAKETANI. Range: Turonian – Coniacian-Santonian?**

correct observation and interpretation of outcrops. In some places (Punta Gorda, Fig. 5D, El Encanto, Fig. 5E) disharmonic, soft-sediment deformation, which can be related to the intrusion of sills into the sediment bodies is observed. This deformation was described by Gursky (1988) and interpreted as a syndiagenetic deformation related to slumping.

In other places more brittle fracturing of semilithified chert beds occurred prior to the intrusion of basalt sills. We observed chilled margins of igneous rocks that rest on surfaces of faults affecting the sediments. Away from the contacts, in the interior of radiolarite bodies, harmonic, chevron folds occur. These could be related to shear within the magmatic pile due to rapid cooling or due to the subsequent emplacement of viscous intrusives into or atop the preexisting magmatic pile. Kuijpers (1980) explained the deformation of the radiolarites by multiphase, alpine-type isoclinal folding, cross-cut by faults. However, no corresponding high temperature metamorphism has been observed. The radiolarite temperatures reach thermometamorfic conditions and they were probably heated to more than 500°C in the contact with intrusive rocks (Gursky and Gursky, 1988). Post-magmatic, further brittle deformation, complicate the geologic framework. Planar shear surfaces are frequent and are lustrous and/or striated, or vein filled, separating both lithologies by sharp contacts. This posterior tectonic deformation adds another difficulty to a reliable interpretation of the rocks of the Nicoya Complex.

GEOLOGIC HISTORY

This section focuses on the different events that occurred chronologically from Middle Jurassic to Paleocene and are relevant to the geologic history of the Nicoya Peninsula. We discuss not only facts but also the lack of consistency of certain hypothesis that have been used to support the models for the genesis and evolution of the Nicoya Complex. The geologic history is synthesized in cartoons (Fig. 9), because the absence of more reliable data to improve part of our model.

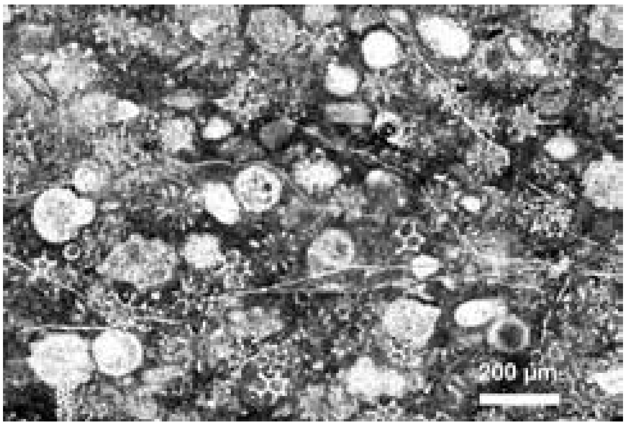


FIGURE 8 **Thin section photomicrograh (Playa Real) of an Early Cretaceous radiolarite, showing the dominance of pantanelliids in the radiolarian assemblage.**

Previous Plateau Event (Mn-radiolarites)

Evidence (from the field and laboratory) discussed above make clear that the Jurassic-Early Cretaceous radiolarites Mn-radiolarites formed on a hypothetical (so far unknown) Early to early Middle Jurassic oceanic crust (Fig. 9A). However no Jurassic geochronologic ages and nor MORB geochemistry have been identified in the Nicoya Peninsula.

The Mn-radiolarites of the Nicoya Complex could have had a similar oceanic basement. Such an ocean crust must have belonged to the Fallaron Plate, and probably formed close to the crust of Site 801 (Fig. 4B), but on the Eastern side of the Ridge, separating the Pacific and Fallaron plates. We interpret the absence of late Bathonian to early Oxfordian, or even early Kimmeridgian radiolarian ages in the Nicoya Complex (Fig. 4A) as an original stratigraphic gap that is comparable to those observed in the Franciscan Geysers Chert and at ODP Site 801 (Fig. 4B). Although the start and duration of the gap varies from site to site, it must represent a common low-latitude Pacific feature. We are aware that this gap could be due to incomplete sampling of the dismembered sediment pile, but is very improbable, considering the intense collecting campaigns we have conducted in the last twenty years.

Beginning of the Caribbean Plateau Event

Basalts first became emplaced on the ocean floor as early as Berriasian-Valanginian (Fig. 9B), as the first magmatic manifestations of the Caribbean Plateau Event (Hoernle et al., 2004). At that time, dikes and sills must have intruded the oceanic basement and the radiolarites (Fig. 9C). This magmatism continued (Fig. 9D), probably in irregular steps of activity thru the 92-88 Ma (Turonian), that represent the major stage of the Nicoyan part of the plateau (Sinton et al., 1997). This is confirmed by the fact that radiolarite sedimentation rarely lasted beyond the Aptian and definitively ceased in the Albian.

With the emplacement of dikes through the ocean floor and its sediment cover, a thermally driven circulation started and leached sedimentary Mn and SiO_2 from the radiolarites, and this formed massive Mn-ore and jasper deposits along sediment/igneous contacts and newly formed fractures.

The main Caribbean Plateau Event

During the Turonian-Coniacian (95.5-88 Ma, Sinton et al., 1997) a few km thick pile of diabases and basalts formed and covered the oceanic basement and the oceanic sediments (Donnely, 1973; Duncan and Hargraves, 1984; Sinton et al., 1998; Fig. 9E). Much of the interstitial water in the radiolarian ooze was probably trapped and sealed in by the igneous rocks. In that way radiolarites that were not in direct contact with the igneous rocks escaped major compaction and metamorphism but underwent, first soft sediment deformation, then accelerated silica diagenesis and hydrofracturing. At this time the radiolarite package became buoyant with respect to the mafic intrusive rocks and further intrusions at the toe of the plateau must have detached the sediments from their crustal substrate by "magmatic floating". This means that the final emplacement of radiolaritic rocks of Nicoya Complex was not tectonic but it was a magmatic consequence of the Caribbean plateau event. Intense brittle deformation and hydro-fracturing and multiphased intrusion of the radiolarites occurred at this time.

Late Phases of the Caribbean Plateau Event (Fe-radiolarites)

The Fe-radiolarites (Coniacian-Santonian) are younger than most of the geochronologically dated basalts and must have formed on top of the plateau (Fig. 9E). Iron-rich hydrothermal waters must have escaped in great quantities into the ocean water in the CLIP area and the settling of a dilute Fe hydroxide suspension must have accompanied the pelagic sedimentation of radiolarians, leading to Fe-rich siliceous deposits (Kuijpers, 1980). Late extrusions into and over the Fe-radiolarites (Fig. 9F) resulted in hydrothermal leaching and precipitation of hematite, limonite and massive jasper, as was described by Kuijpers and Denyer (1979).

Late Santonian/Early Campanian tectonic event

Shortly after the emplacement of the Caribbean plateau, the area underwent a compressional event that caused profound deformation and uplift that corresponds to the N-Nicoya Peninsula and the Santa Elena Peninsula. This tectonic event created the Santa Elena overthrust (Azéma and Tournon, 1980), and the tectonic mélanges that are found beneath that thrust. Major nappes have been proposed also for the NW Nicoya Peninsula (Kuijpers, 1980; Azéma et al., 1984; Bourgois et al., 1984 . However, detailed mapping (Fig. 2) has not confirmed the evidence of these thrust contacts. A thick sedimentary post-Campanian sequence overlapped the Oceanic assemblages.

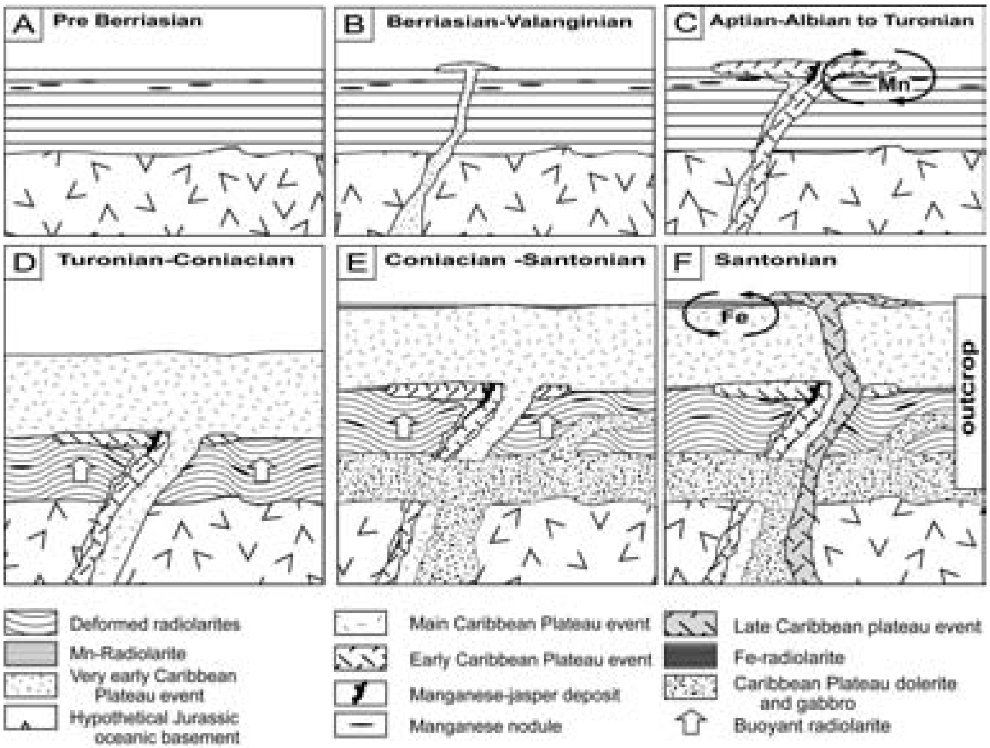


FIGURE 9 | **Synopsis of Middle Jurassic to Late Cretaceous events that led to the formation of the Nicoya Complex drawn in schematic cross-sections (not to scale). We infer the emplacement of a plateau belonging to the CLIP (Caribbean Large Igneous Province) on a hypothetical Early to early Middle Jurassic oceanic crust, and "magmatic floating" of Jurassic-Cretaceous radiolarites.**

CONCLUSIONS

At first glance, Ar^{39}/Ar^{40} magmatic radioisotopic data (Cretaceous) and the Mg-radiolarite ages (Jurassic-Early Cretcaceous) in N-Nicoya result in an incoherent picture of blocks set in a magmatic "matrix". However, chilled margins of the magmatites, and hydrothermal baking and leaching of the sediments along contacts confirm the Ar^{39}/Ar^{40} dating, in that igneous rocks are consistently younger than most of the radiolarian cherts. No Jurassic oceanic basement has been identified so far at the outcrop level in the Nicoya Peninsula. We solve the misunderstanding using a unique possible model, in which the Jurassic-Cretaceous chert sediment pile became disrupted and detached from its original basement, by multiple intrusions during the formation of the "Nicoya Plateau". Hypothetically, the Early Jurassic magmatic basement could be found beneath the surface, covered by the kilometer thickness of the magmatic pile of the plateau event (Fig. 9). Also, some exotic blocks of the Jurassic basement originally underlying the radiolarite could be preserved as fragments in the Plateau magmatics; but these could be rare in N-Nicoya.

If we reconstruct the radiolarite section from individual blocks (Fig. 4) a late Middle Jurassic stratigraphic gap appears. This feature is common in the oceanic sections known from the Pacific, namely at ODP Site 801 and in the Main Headlands Terrane of California (Bartolini and Larson 2001; Murchey, 1984). This fact together with the typical Pacific affinity of the Jurassic radiolarian faunas confirms the Pacific origin of Nicoya Complex.

We cannot confirm or reject the existence of nappe structures in the Nicoya Peninsula. However, soft sediment deformation in the radiolarites occurred, at least partially, during early stages of intrusion and formation of the Plateau. Pervasive brittle faulting and local formation of tectonic mélanges must have occurred during later stages of Plateau formation and/or during the late Campanian collision event.

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