Accretionary history and magma sources in the Southern Andes.

RAPELA, C.W. Centro de Investigaciones Geológicas, Universidad Nacional de La Plata, Calle 1 N° 644, 1900 La Plata, Argentina

Summary

The crustal framework of the southern Andes was formed during Early Paleozoic continental collisions that completed the amalgamation of southwest Gondwana. At least two major episodes of subduction were associated with these events, during the Early Cambrian (*ca.* 530 Ma) and the Early to Middle Ordovician (465–490 Ma), preceding the accretion of micro-continents that caused the lateral -westward- growth of the supercontinent. In order to assess the role of mantle and crust during the Phanerozoic construction of the Andean orogen, new initial Sr and Nd isotopic ratios and geochemical data from plutonic rocks of different ages are presented, along an integrated 700 km cross-section of the Andes at 30°–34°S. The combined isotopic and geochemical evidence indicates that while Early Paleozoic events reworked an Paleo- to Meso-proterozoic lithosphere, the Late Paleozoic Pacific subduction regime established at *ca.* 290–320 Ma on accreted Grenvillian crust, involved reworking of a Meso- to Neo-proterozoic lithosphere. Mesozoic–Tertiary Andean subduction represents a radical change in this trend, as it is characterized by melting of relatively young depleted sources, probably associated with the different plate dynamics that began to prevail during and after the break-up of Gondwana in Jurassic–Early Cretaceous times.

Introduction

Cordilleran I-type batholiths emplaced in convergent environments involving subduction of an oceanic plate behind a continental margin are commonly referred as "Andinotype", as the Andes are the classical setting for these granites (e.g. Pitcher 1987). Their origin is usually linked to cycling of mantle underplated material, therefore they are a key issue in continental growth. In the Andes, subduction arrangement and dynamics largely changed in Early Cretaceous times, *ca.*130 Ma, as a result of the final break up of Gondwana with the opening of the South Atlantic. The large Mesozoic–Tertiary batholiths formed during this episode, such as the Coastal Batholith of Peru, the Coastal Batholith of central Chile and the Patagonian Batholith, are major examples frequently used for comparison in geological and petrological studies. Recent isotopic studies in several of these bodies indicate very little continental crustal participation -if any- in the source of the granites, which is dominated by primitive compositions (Pankhurst *et al.* 1999; Parada *et al.* 1999).

However protracted, the period of convergence during which these typical Andean batholiths were emplaced was only the last of the complex and episodic history of the Andes, which started in Cambrian times with the assembly of Gondwana. A remarkable foreland uplift at 30°–33°S has resulted in mountain blocks located up to 800 km from the present trench. This has allowed detailed studies of the pre-Silurian basement and definition of the orogenic-accretional events that developed the crustal framework of the Southern Andes (Pankhurst *et al.* 1998; Rapela *et al.* 1998, 1999). Together with previous results, new geochemical and Sr-Nd isotopic data are presented in order to assess the role of mantle input during the Phanerozoic construction of the Andean orogen, and its relation to episodes of terrane accretion.

Early Paleozoic margins: the Pampean and Famatinian orogenies

Paleozoic provinces at 27°–33°S may be divided into those related to Early to Middle Cambrian accretion (the Pampean mobile belt), those associated with Ordovician subduction (the Famatinian mobile belt), and exotic terranes accreted during later collisions (the Precordillera terrane and Grenvillian fragments) (Fig. 1). In the Sierras de Córdoba at 32°S (Fig. 1), the Pampean orogeny started with emplacement of subduction-related calc-alkaline granitoids at 530 ± 4 Ma, followed by rapid crustal thickening to granulite conditions, decompression and final intrusion of strongly peraluminous granites and associated cordieritites at 523 ± 2 Ma. This orogeny is interpreted as due to Early to Middle Cambrian collision between the semi-autochthonous Pampean terrane and Gondwana (Rapela *et al.* 1998).

The Famatinian magmatic arc was initiated in earliest Ordovician time and affected all geological provinces in southwestern Gondwana (Fig. 1) (Pankhurst *et al.* 1998). New U-Pb SHRIMP ages for the Famatinian granites indicate that the age of all units falls in the range 468–486 Ma, and this is only increased to 465–495 Ma at the extreme range of estimated errors (Rapela *et al.* 1999). Although roughly coeval, the Famatinian granitoids show a regular geographical distribution of compositional types: (a) Medium to small sized bodies of high-Na tonalites, trondhjemites and granodiorites were emplaced in the easternmost side of the orogen, along the older Pampean belt (Sierras de Córdoba, Fig. 1); (b) low-Ca peraluminous batholiths and small bodies of cordierite-bearing monzogranite were emplaced *in situ* at shallow depths, in high-T, low-P metamorphic rocks cropping out along the central sector of the Famatinian belt; and (c) I-type, calcic metaluminous suites, from gabbro to high silica leucogranite, were emplaced along the western side of the Famatina belt (Sierras de Malanzan, Chepes, Los Llanos and Valle Fertil, Fig. 1). Volcanic rocks are also conspicuous to the north of this belt.

Accreted terranes: the Precordillera terrane and associated Grenvillian fragments

The waning of the Famatinian arc during the Middle Ordovician heralded the approach of the Precordillera terrane (PT) to the proto-Andean margin. The PT is recognized as a major continental fragment rifted from the southern Appalachian region in Laurentia and accreted to the western margin of Gondwana (see Thomas & Astini 1999 for references). It is composed of Cambrian–Early Ordovician platform sediments overlying a Precambrian basement that was originally dated at 1102 ± 6 Ma by conventional U-Pb in samples from xenoliths in Tertiary plutons (Kay *et al.* 1996). Rb-Sr whole rock isochrons of 1030 ± 30 and 1021 ± 12 Ma have been obtained in granitic orthogneisses from adjacent basement outcrops to the east of the Precordillera in the Sierra de Pie de Palo and Sierra de Umango. This suggests a wide distribution of the Grenvillian basement of the PT (Varela *et al.* 1996; Pankhurst & Rapela 1998). The extent of the PT and the number of Grenvillian fragments are still a matter of debate. However, the recent findings of Grenvillian basement in La Pampa at 37°S (Sato *et al.* 1999), and in the basement of the Frontal Cordillera to the west of Precordillera (Ramos & Basei

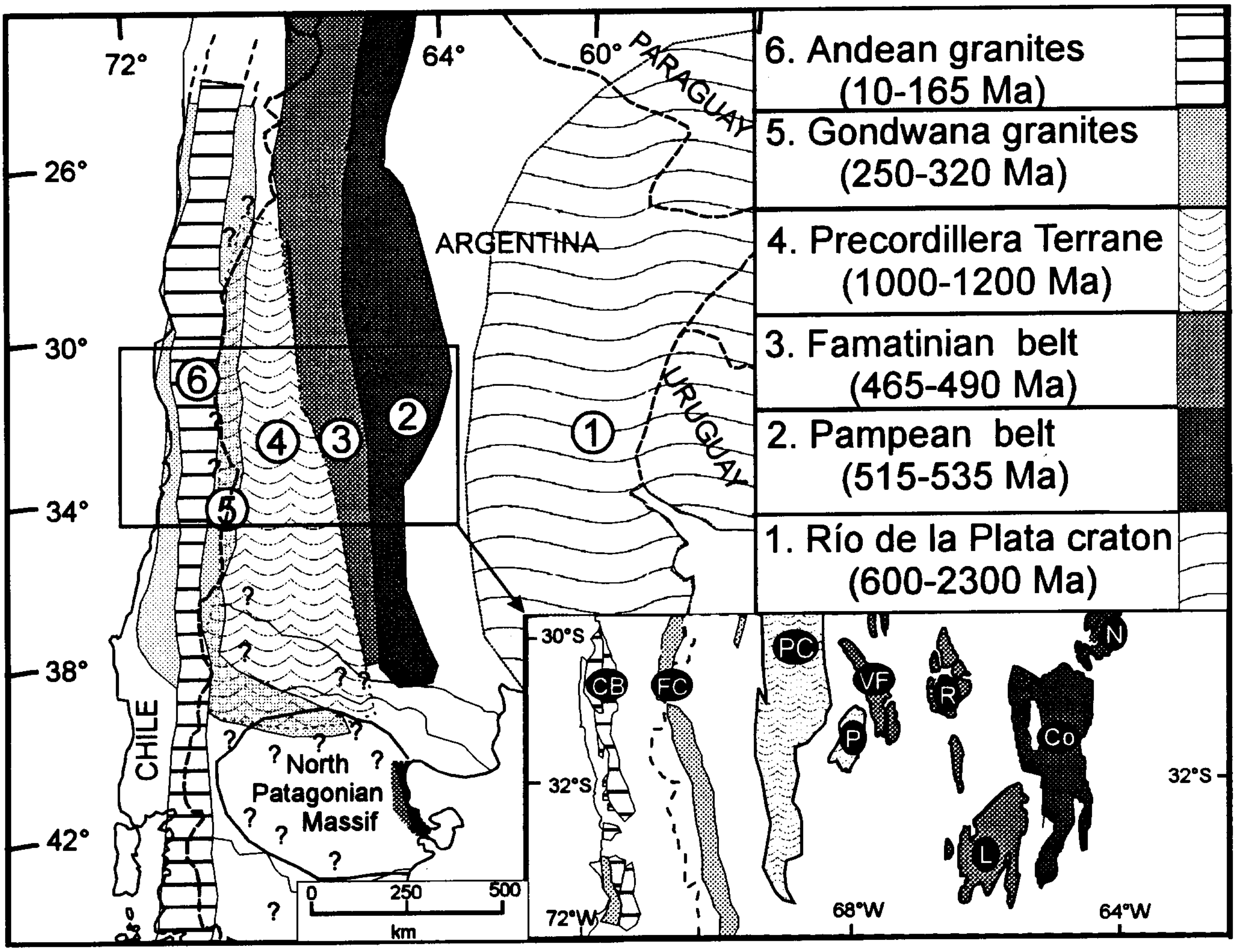

Fig. 1: Main Paleozoic and Mesozoic units in the Southern Andes, 30–34°S. Principal Sierras and batholiths in this segment are: N: Sierra Norte de Córdoba; Co: Sierra de Córdoba; L: Sierra de San Luis; R: Sierras de Los Llanos, Malanzán y Chepes; VF: Sierra de Valle Fértil; P: Sierra de Pie de Palo; PC: Precordillera; FC: Batholiths of the Frontal Cordillera; CB: Coastal Batholith of central Chile.

1997), suggest that similar basement underlies most of central Chile and reaches at least as far as northern Patagonia (Fig. 1).

Gondwanian plutonism (Carboniferous–Jurassic)

Intrusion of large post-orogenic Devonian batholiths in the southern Sierras Pampeanas and Patagonia followed the Early Paleozoic orogenies and accretionary of Grenvillian basement fragments. The period of maximum extent and relative stability of the Gondwana supercontinent ranges from Carboniferous to final break up in Early Cretaceous time (Pankhurst & Rapela 1998). Intrusion of Carboniferous Cordilleran-type batholiths in the accreted Grenvillian terranes is associated with the starting of a new subduction regime along the paleo-Pacific margin. Development of extensive Permian to Jurassic rhyolitic provinces and inner cordilleran plutonic belts are characteristic of the Gondwanian magmatism. At 33°S, Late Paleozoic batholiths occur both in the coast range of Chile and in the Frontal Cordillera (Fig. 1), suggesting that no major continental accretion took place after the docking of the PT and associated Grenvillian terranes. In the Frontal Cordillera of Argentina, the Colangüil batholith records intrusive activity from 329 Ma to 247 Ma (mineral Rb-Sr ages, Llambías & Sato 1995). In central Chile, the Carboniferous batholiths were followed by pulses at *c.* 200 Ma and 165 Ma, which preceded emplacement of the typical Cretaceous Andean granites at 90–130 Ma (Parada *et al.* 1999).

Isotopic and chemical cross-section of the Andes at 30°–34°S

Initial Sr and Nd isotope ratios and the main geochemical characteristics of gabbro to leucogranite plutonic rocks from an integrated 700 km cross-section of the Andes at 30°–34°S are shown in Fig. 2. Sixty seven samples from the Cambrian (Pampean) and Ordovician (Famatinian) episodes and 23 samples from the Carboniferous to Cretaceous plutonism of central Chile (the latter from Parada *et al.* 1999), are considered representative of the age and composition of the southern Andean crust. The Cambrian and Ordovician rocks show contrasting chemical and isotopic characteristics when compared with the younger Andean bodies. The older plutonic rocks show a wide silica range (Fig. 2a) and, although metaluminous I-type varieties from gabbro to granodiorites are abundant, cordierite-bearing S-type granites are also conspicuous (S-type granites show Alumina Saturation Index greater than 1.1, Fig. 2b). S-type granites are rare in the Carboniferous to Cretaceous granites, indicating that melting of sedimentary material was not frequent in these episodes. The εNd_t

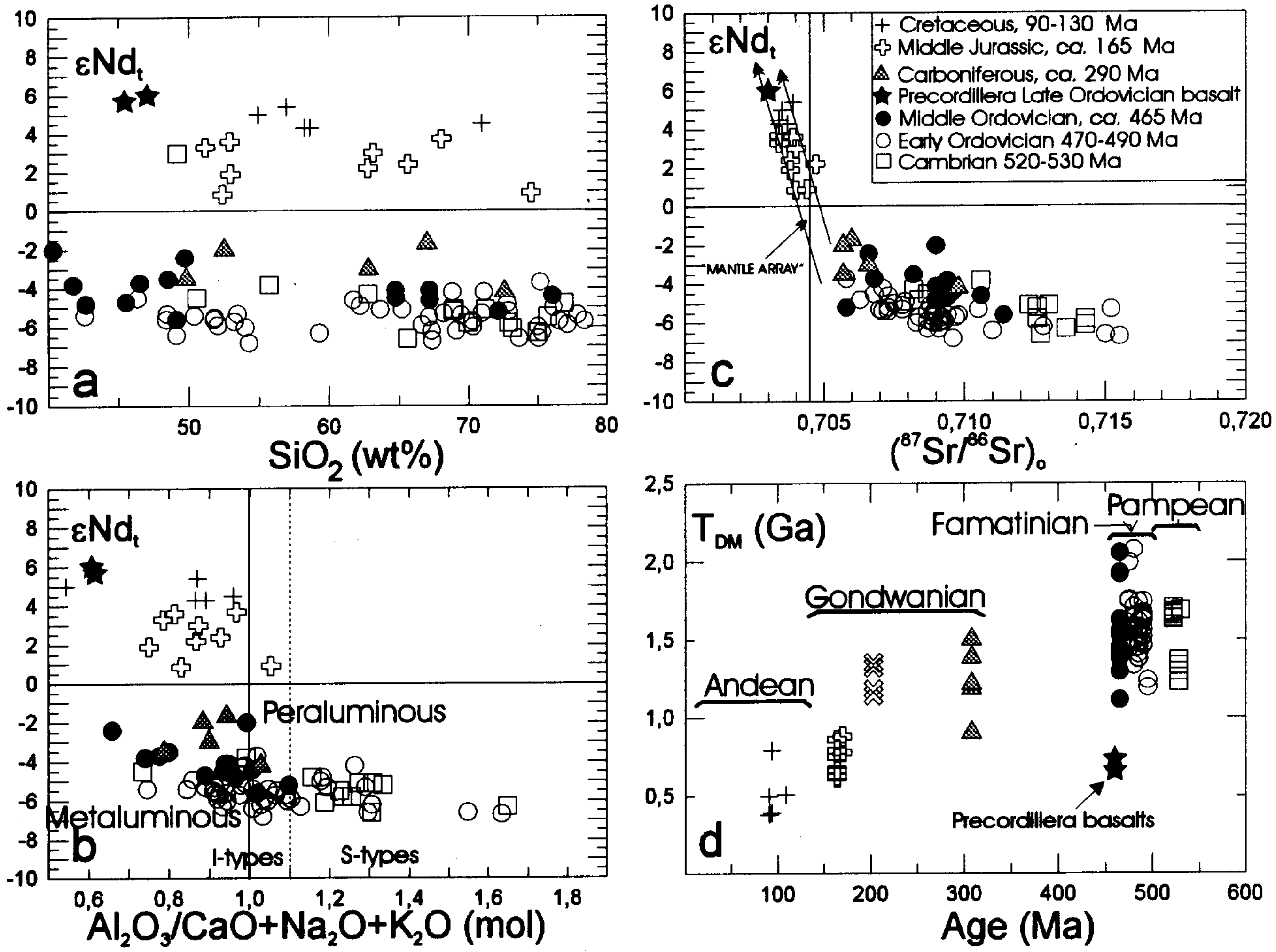

Fig. 2: Plots for granitic rocks emplaced during the main convergence and orogenic episodes in the Andean sector at 28°-33° S: (a, b, c) SiO_2 (wt%), $(^{87}Sr/^{86}Sr)_0$, and Al_2O_3 / $CaO+Na_2O+K_2O$ (mol) vs. εNd_t; and (d) Emplacement age vs. Depleted mantle model age (T_{DM}, Ga). Data for Carboniferous, Jurassic and Cretaceous granites in Chile are from Parada et al. (1999). The dashed line in Fig. 2b separates coeval Early Paleozoic I- and S-type granites.

value decreases with time (Fig. 2a), suggesting derivation from progressively more primitive and depleted sources. Only the younger Gondwanian and the Cretaceous granites plot in the "mantle array" of the $(^{87}Sr/^{86}Sr)_0$ – εNd_t isotopic relationships, in contrast to the Paleozoic granites, all of which lie outside the mantle field, with $\varepsilon Nd_t < -2$ (Fig. 2c). This is a remarkable feature of the Cambrian and Ordovician events, as they include abundant amphibole-bearing and noritic gabbros with less than 50% SiO_2, that share the same crustal signature as the intermediate rocks (Fig. 2a). As there is no evidence for massive *in situ* contamination during emplacement in the upper crust, this signature must reflect the composition of the middle or lower crust (Pankhurst *et al.* 1998). Depleted mantle model ages (T_{DM}) for most of the Cambrian and Ordovician rocks, both I- and S-types, are in the interval 1400–1700 Ma indicating derivation from a Paleo- to Meso-proterozoic source (Fig. 2d). Altogether the chemical and isotopic evidence suggests that the Pampean and Famatinian episodes did not involve significant recycling of young underplated material. Rather, it indicates melting of an old crustal section, including the underlying subcontinental mantle, to produce the basic rocks with enriched isotopic signatures. An obvious candidate with these characteristics is the Rio de la Plata craton (Fig. 1). Note that the Late Ordovician pillow lava basalts of the western side of the Precordillera show very depleted MORB-like isotopic signatures (Fig. 2d), very different from their continental plutonic counterparts within the same silica range. This again indicates that recycling of young Ordovician underplated basalts was not the source of the Early Paleozoic I-type magmatism. Although isotopically less evolved than the Cambrian–Ordovician granites, the Carboniferous coastal batholiths of Chile also plot outside the "mantle array", but with younger (mostly Neoproterozoic) model ages (Figs. 2c, d). Recycling of the immature 1000–1200 Ma Grenvillian crust in which they are emplaced (Fig. 1) seems to fit the source isotopic constraints. Only the Andean and younger Gondwanian granites show depleted signatures (Fig. 2) (Parada *et al.* 1999): this is not only a characteristic of central Chile but also of the Patagonian Andes (Pankhurst *et al.* 1999).

Conclusions

The Proto-Andean subduction and collision/accretion episodes that form the crustal framework of the Andes are characterized by reworking of old continental lithosphere. I-type metaluminous Paleozoic rocks show enriched isotopic signatures derived from melting of old lower crustal mafic granulites and associated continental mantle. Magma sources changed with time during the Paleozoic as the supercontinent grew westwards by lateral accretion of Grenvillian micro-continental fragments such as the Precordillera terrane. While the Early Paleozoic events reworked Paleo- to Meso-proterozoic lithosphere, the new Late Paleozoic Pacific subduction regime established on the accreted crust involved reworking of Meso- to Neo-proterozoic lithosphere. The Mesozoic–Tertiary Andean subduction episode represents a radical change in this trend, as they are characterized by melting of relatively young depleted sources, probably associated with the different plate dynamics that started during and after the break up of Gondwana.

Acknowledgements

Funds were provided by CONICET grant PIP 4148 and FONCYT grant PICT 4189. Robert Pankhurst kindly reviewed the manuscript.

References

Kay, S. M., Orrell, S., and Abruzzi, J. M. 1996. Zircon and whole-rock Nd-Pb isotopic evidence for a Grenville age and Laurentian origin for the basement of the Precordillera in Argentina. Journal of Geology, 104: 637-648.

Llambías, E.J. and Sato, A.M., 1995. El batolito de Colangüil: transición entre orogénesis y anorogénesis. Revista de la Asociación Geológica Argentina, 50: 111-131.

Pankhurst, R. J., and Rapela, C. W. 1998. The proto-Andean margin of Gondwana: An introduction. In *The Proto-Andean margin of South America,* eds Pankhurst, R. J., and Rapela, C. W., pp. 1-9. Geological Society [London] Special Publication 142.

Pankhurst, R. J., Rapela, C. W., Saavedra, J., Baldo, E., Dahlquist, J., Pascua, I. and Fanning, C. M. 1998. The Famatinian magmatic arc in the central Sierras Pampeanas. In *The Proto-Andean margin of South America,* eds. Pankhurst, R. J., and Rapela, C. W., pp. 343-367. Geological Society [London] Special Publication **142**.

Pankhurst, R.J., Weaver, S.D., Hervé, F. and Larrondo, P. 1999. Mesozoic–Cenozoic evolution of the North Patagonian Batholith in Aysén, southern Chile. Journal of the Geological Society, London, 156: 673-694.

Parada, M.A., Nyström, J.O. and Levi, B., 1999. Multiple sources for the Coastal Batholith of central Chile (31-34°): geochemical and Sr-Nd isotopic evidence and tectonic implications. Lithos, 46: 505-521.

Pitcher, W.S., 1987. Granites and yet more granites forty years on. Geologische Rundschau, 76: 51-79.

Ramos, V. A., and Basei, M. 1997. The basement of Chilenia: an exotic continental terrane to Gondwana during the early Paleozoic. In *Terrane Dynamics -97: International Conference on Terrane Geology,* eds Bradshaw, J. D., and Weaver, S. D., pp. 140-143. University of Canterbury, Christchurch, Conference Abstracts.

Rapela, C. W., Pankhurst, R. J., Casquet. C., Baldo, E., Saavedra, J., Galindo, C. 1998. Early evolution of the proto-Andean margin of South America. Geology, 26: 707-710.

Rapela, C. W., Pankhurst, R. J., Dahlquist, J. and Fanning, C.M. 1999. U-Pb SHRIMP ages of Famatinian granites: new constraints on the timing and tectonic setting of I- and S-type magmas in an ensialic arc. In *II South American Symposium on Isotope Geology,* pp. 264-267, Carlos Paz, Argentina, Conference abstracts.

Sato, A. M., Tickyj, H., Llambías, E. J. and Sato, K., 1999. Rb-Sr, Sm-Nd and K-Ar age constraints of the Grenvillian Las Matras pluton, central Argentina. In *II South American Symposium on Isotope Geology*, pp. 122-126, Carlos Paz, Argentina, Conference abstracts.

Thomas, W.A. and Astini, R.A., 1999. Simple-shear conjugate rift margins of the Argentine Precordillera and the Ouachita embayment of Laurentia. Geological Society of America Bulletin, 111: 1069-1079.

Varela, R., López de Luchi, M., Cingolani, C. and Dalla Salda, L., 1996. Geocronología de gneises y granitoides de la Sierra de Umango, La Rioja. Implicancias tectónicas. XIII Congreso Geológico Argentino y III Congreso de Exploración de Hidrocarburos, Buenos Aires, Actas III, 519-527.