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## **DOCTOR OF PHILOSOPHY**

**The role of the apoplast as an osmotic compartment in *Suaeda maritima* L. Dum. and *Beta vulgaris* L.**

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**The Role of the Apoplast as an Osmotic  
Compartment in *Suaeda maritima* L.  
Dum. and *Beta vulgaris* L.**

by

***Ruth Ann Lawrence***

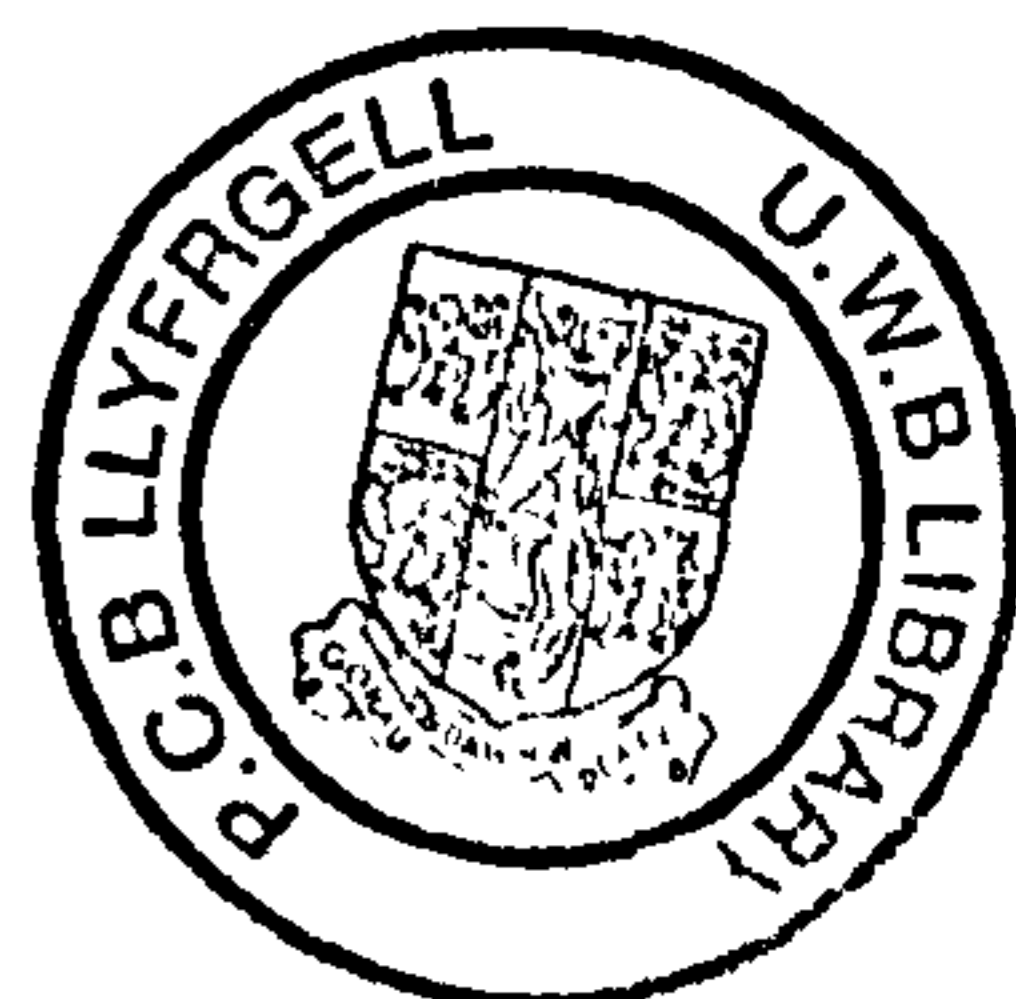
under the supervision of

***Prof. A. Deri Tomos***

A thesis prepared for the University of Wales  
Bangor for the degree of Doctor of Philosophy

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## Abstract

The plant cell wall is a living and dynamic compartment of the plant cell. Its many diverse functions range from cell expansion and differentiation to defence and signalling. Furthermore, there is currently a growing body of evidence which suggests that the cell wall/apoplast also plays an important role in cell water relations. The aim of this study was to highlight the importance of apoplastic solutes in plant cell water relations, particularly in turgor regulation.

The water relations parameters of two members of the family *Chenopodiaceae*, *Suaeda maritima* L. Dum. and *Beta vulgaris* L., were studied at single cell resolution using the cell pressure probe, single cell sampling and analysis techniques, and the xylem pressure probe. These species share a common peculiarity, in that certain cell types, namely the leaf epidermal cells in *Suaeda maritima* and the taproot storage parenchyma cells in *Beta vulgaris*, maintain cell turgor pressure ( $P_{\text{cell}}$ ) at a level which is dramatically lower than the respective cell osmotic pressures ( $\Pi_{\text{cell}}$ ). This phenomenon is attributed to the properties of the cell wall/apoplast. The hydrostatic component of the apoplast ( $P_{\text{wall}}$ ) accounts for only a small fraction of the difference between  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  in these species. In light of this the discrepancy between  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  can only be due to the presence of osmotically active solutes in the adjacent apoplast ( $\Pi_{\text{wall}}$ ).

*Suaeda maritima* leaf epidermal cells accumulate NaCl in response to an increase in external NaCl concentration. This accumulation of solutes leads to an increase in leaf epidermal osmotic pressure, which exactly mirrors the increase in the osmotic pressure of the external medium ( $\Pi_{\text{ext}}$ ). Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ), however, is maintained at a constant level over a range of external salinities. In the short term the leaf epidermal cells are shielded from abrupt changes in  $\Pi_{\text{ext}}$  by the properties of the root system, and a root reflection coefficient which is close to 0. In the longer term, as NaCl accumulates in the protoplast,  $P_{\text{cell}}$  is apparently maintained by the parallel adjustment of solutes in the protoplast and apoplast.

Changes in *Suaeda maritima* leaf epidermal turgor pressure ( $P_{\text{cell}}$ ), induced by modulating the solute content of the apoplast ( $\Pi_{\text{wall}}$ ) in excised leaves, initiated a mechanism which regulated  $P_{\text{cell}}$  back to *in vivo* levels within 40 minutes. Turgor regulation was not accompanied by equivalent changes in cell osmotic pressure ( $\Pi_{\text{cell}}$ ), suggesting that osmotic adjustment leading to turgor regulation is apoplastic rather than protoplasmic in nature. This apoplastic osmotic adjustment mechanism was dependent on the permeant nature of the apoplastic solutes and on the volume of the apoplast. A comparable upward turgor regulation mechanism was observed in excised *Beta vulgaris* taproot tissue, within 40 - 80 minutes. The presence of apoplastic  $K^+$  apparently facilitated the turgor regulation mechanism in this case. Proton efflux studies on *Beta vulgaris* taproot tissue revealed that the driving force behind this osmotic adjustment mechanism is likely to be turgor/external osmotic pressure ( $P_{\text{cell}}/\Pi_{\text{ext}}$ ) dependent modulation of plasma membrane proton ATPase activity. It was concluded that the apoplast should be regarded as a true osmotic compartment in higher plants.

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## List of abbreviations

<b>Abbreviation</b>	<b>Definition</b>
$\Delta$	Difference/change in
EB	Erythrosin B
EDX	Energy dispersive X-ray microanalysis
$\phi$	Osmotic coefficient
FC	Fusicoccin
g	Acceleration due to gravity
h	Height/depth
P	Hydrostatic pressure
$P_{\text{cell}}$	Cell turgor pressure
$\Pi_{\text{cell}}$	Cell osmotic pressure
PCMPS	p-Chloromercuriphenylsulphonic acid
$\Pi_{\text{ext}}$	Osmotic pressure of the external medium/osmoticum
$P_{\text{wall}}$	Hydrostatic component of the apoplast/cell wall
$\Pi_{\text{wall}}$	Osmotic component of the apoplast/cell wall
$P_{\text{xylem}}$	Xylem pressure/tension
$\rho$	Density of liquid
$\sigma$	Cell/membrane reflection coefficient
$\sigma_r$	Radial reflection coefficient
TS	Transverse section

To Howard M. Jones.



## Chapter 1 : Introduction

### 1.1, The plant cell wall

One of the most striking features of plant cells is the cell wall. All plant cells (except the sperm and some egg cells) have walls (Mauseth, 1988). Plant cell walls are persistent, being preserved very well during specimen preparation and even in death. In trees, most of the wood and bark is composed of cell walls, the actual protoplast having perished. In woody plants, the walls constitute the majority of the plant body (Mauseth, 1988).

The first detailed microscopic observations of plant cell walls were made in the seventeenth century by the gentleman scientist Robert Hooke. Robert Hooke was one of the greatest experimental scientists of his time. His interests knew no bounds, ranging from physics and astronomy, to chemistry, biology and geology, to architecture and naval technology. He collaborated, or corresponded, with scientists as diverse as Christian Huygens, Antony Van Leeuwenhoek, Christopher Wren, Robert Boyle, and Isaac Newton. Among other accomplishments, he invented the universal joint, the iris diaphragm, an early prototype of the respirator, the anchor escapement and the balance spring (which facilitated the production of accurate time pieces). Hooke also served as Chief Surveyor and helped rebuild London after the Great Fire of 1666. He worked out the correct theory of combustion, assisted Robert Boyle in working out the physics of gases, worked out the physics of elastic materials, invented or improved meteorological instruments such as the barometer, anemometer and hygrometer; and the list goes on (see Newbold, 1969).

Hooke's reputation as a biologist rests largely on his book *Micrographia*, published in 1665. Hooke devised the first compound microscope (one of the finest microscopes of his time) and, with its novel illumination system, observed objects as diverse as insects, sponges, bryozoans and bird feathers. His drawings and detailed observations were truly magnificent. Perhaps Hooke's most famous microscopical observation was his study of thin slices of cork. He wrote: "... *I could exceedingly plainly perceive it to be all*

*perforated and porous ... these pores or cells, ... were indeed the first microscopical pores I ever saw, and perhaps, that were ever seen, for I had not met with any writer or person, that had made any mention of them before this*" (Hooke, 1665). Hooke had discovered plant cells, and indeed was the first to coin the term "cell", taken from the Latin, meaning little room. The "little rooms" Hooke described so beautifully were in fact only the ghostly remains of plant cells; the structures he viewed under his microscope were actually the plant cell walls of cells long perished.

Historically, the plant cell wall was treated as a non-living, inert secretion, that was not truly a part of the living cell. However, our current understanding portrays the wall as a dynamic, metabolically active cellular compartment, equal in status to the cytoplasm and vacuole. The plant cell wall is actively involved in defence, detoxification, signalling, cell-to-cell recognition, cell expansion, cell adhesion, cell separation, translocation, differentiation, morphogenesis (Cosgrove, 1997 and references therein), and cell water relations (this study).

## **1.2, Plant cell wall structure and properties**

The plant cell wall is a highly complex structure, made of polysaccharides, lignin, cutin, suberin, waxes, protein, enzymes, calcium, boron, and water, that has the ability to self assemble (Carpita and Gibeaut, 1993; Cosgrove, 1997). Cell wall differentiation has enabled plants to exploit and conquer almost every microclimate on the planet. Key examples of wall differentiation include, the development of xylem and phloem transport systems; the formation of a waxy cuticle that prevents desiccation; the production of spores with cell walls impregnated with sporopollenin, a substance that prevents desiccation and is virtually completely micro-organism resistant; stems which have both rigid and flexible properties; the incorporation of lignin to provide mechanical support; and the formation of bark from specialised cork cambium (for a review on the morphology and evolution of vascular plants see Gifford and Foster, 1989).



### 1.2.1, Cellulose

Cellulose is the most abundant polysaccharide on the planet and is an essential component of the primary cell wall of plant cells (approximately 30 % of the primary cell wall is made up of cellulose - see Cosgrove, 1997). Cellulose is composed entirely of  $\beta$ -glucose monomers joined in 1-4 linkages. Parallel chains of cellulose molecules are bound together, via hydrogen bonding between hydroxyl groups on the  $\beta$ -glucose monomers, forming cellulose units or aggregates called microfibrils (Carpita and Gibeaut, 1993; Cosgrove, 1997). Cellulose microfibrils are between 5 and 15 nm wide and are spaced 20 - 40 nm apart (McCann *et al.*, 1990). The microfibril framework forms the main architectural component of the primary plant cell wall (Carpita and Gibeaut, 1993; Cosgrove, 1997). Cellulose has a very high tensile strength, which is equivalent to that of steel; this remarkable property of cellulose is due to its structure (Wainwright *et al.*, 1976).

### 1.2.2, Hemicellulose

The hemicelluloses are complex polysaccharides which are tightly bound in the primary cell wall (Cosgrove, 1997). The principal hemicellulose in the cell walls of flowering plants is xyloglucan - a branched polymer consisting of a backbone of 1-4 linked  $\beta$ -glucose monomers, with short side chains containing xylose, galactose, and frequently, a terminal fucose (McNeil *et al.*, 1984; Fry, 1989). Xyloglucans are arranged parallel to the cellulose microfibrils and apparently bind to and interlock the cellulose framework (Carpita and Gibeaut, 1993).

### 1.2.3, The pectin matrix

The fundamental cellulose-hemicellulose framework of the plant cell wall is embedded in a matrix of pectin polysaccharides (Carpita and Gibeaut, 1993). Pectins are polymers of the carbohydrate galacturonic acid and its derivatives. The chemical complexity of pectin polysaccharides varies considerably, for example, homogalacturonan is a simple linear polymer of (1-4)  $\beta$ -galacturonic acid, with occasional rhamnosyl residues which



distort the chain, whereas rhamnogalacturonan 1 (RG 1) has a more complex structure of repeating (1-2)  $\alpha$ -L-rhamnosyl and (1-2)  $\alpha$ -D-galacturonyl disaccharide subunits, with long side chains of arabinans and arabinogalactans (Carpita and Gibeaut, 1993; Cosgrove, 1997).

The esterification and de-esterification of pectins affects their physical properties. Many of the acidic residues associated with pectins are esterified with methyl, acetyl, and other unidentified groups (Kim and Carpita, 1992; McCann *et al.*, 1994). Such esterification occurs during pectin biosynthesis in the Golgi apparatus, and may be removed by esterases in the wall (Cosgrove, 1997). De-esterification creates carboxyl groups, thus increasing the charge density in the wall, which may, in turn, influence the activity of wall enzymes (Moustacas *et al.*, 1991). De-esterification promotes the assembly of helical pectin chains into a highly hydrated, gelatinous mesh by facilitating the formation of  $\text{Ca}^{2+}$  bridges, called “junction zones” (Rees, 1977), linking two anti-parallel pectin chains (Carpita and Gibeaut, 1993).

The pectin polymers are thought to perform many functions (Roberts, 1990). They apparently determine wall porosity, provide charged surfaces that modulate wall pH and ion balance (Roberts, 1990), and serve as recognition molecules that signal appropriate developmental responses to symbiotic organisms, pathogens and insects (McNeil *et al.*, 1984).

#### 1.2.4, Structural proteins

In addition to the polysaccharides described above, structural proteins are also incorporated into the primary plant cell wall (Showalter, 1993; Cassab, 1998). These structural wall proteins are classified according to their predominant amino acid composition, for example, hydroxyproline-rich glycoproteins (HRGP), glycine-rich proteins (GRP), proline-rich proteins (PRP) and so on (Cassab, 1998). The most extensively studied group of wall proteins are the hydroxyproline-rich glycoproteins, which include a family of proteins called extensins. The extensins are important structural wall proteins which also apparently play a role in development, wound healing, and plant defence (Cassab, 1998). In dicots, extensins are expressed in

response to wounding, fungal infection, viral infection, fungal elicitors, endogenous elicitors, ethylene, red light, heat shock, gravity, tensile stress, glutathione and cell culturing (Showalter, 1993; Jose and Puigdomenech, 1993; Shirsat *et al.*, 1996 {a} and {b}).

Glycine-rich proteins are a newly discovered class of plant cell wall proteins. These are commonly localised in the vascular bundles, particularly xylem elements, and are clearly associated with cells that are going to be lignified (Showalter, 1993). In light of this, it is proposed that they play a key role in the development of vascular tissues (Cassab, 1998). The expression of these proteins is also induced by viral infection, salicylic acid, abscisic acid, drought stress, and wounding (Showalter, 1993).

Finally, proline-rich proteins also represent a relatively newly discovered class of plant cell wall proteins. They apparently participate in several aspects of development and wall differentiation, including xylem, nodule and pod differentiation, and ovary, embryo and microspore development (Cassab, 1998). In common with other wall protein groups, discussed above, proline-rich proteins are expressed in response to a number of external stimuli, such as wounding, endogenous elicitors, fungal elicitors, ethylene, light, red light and cell culturing (Showalter, 1993).

### **1.2.5, Cell wall enzymes**

The cell wall is a metabolically active compartment of the cell (Cosgrove, 1997). Numerous enzymes have been found to be associated with the cell wall (Cassab and Varner, 1988; Fry, 1995). Four broad classes of reactions are catalysed by wall enzyme activities, hydrolysis (of glycosidic, ester, and peptide bonds), transglycosylation, transacylation (possibly involved in the synthesis of cutin), and redox reactions involving the electron acceptors  $O_2$ ,  $H_2O_2$ , and  $NAD^+$ , and electron donors such as phenols, ascorbate, polyamines, and malate (see Fry, 1995).

Some enzymes act on the structure of the cell wall, for example, endoglucanases, xylosidases, pectinases, pectin methyl esterases, and xyloglucan endotransglycosylases modify the polysaccharide components of the cell wall (Fry, 1995). Peroxidases are



involved in lignification, extensin monomer cross-linking, and the repair of damaged walls (Vance *et al.*, 1980; Cassab and Varner, 1988; Bowles, 1990). While enzymes, such as the chitinases and (1-3)  $\beta$ -glucanases are designed to counter bacterial and fungal pathogen attack (Bowles, 1990).

### 1.2.6, Lignin

Lignin is a strengthening material that occurs in the cell walls of higher plants. It is one of the most abundant biopolymers on Earth (second only to cellulose), and is resistant to degradation by most micro-organisms (Kirk, 1971). Lignin is generally laid down between cellulose microfibrils, and provides mechanical support to plant tissues (Gould, 1983). The formation of lignin is considered by evolutionists to have been crucial in the adaptation of plants to a terrestrial environment, as it is an essential component of the rigid xylem vessel system, necessary to conduct water and mineral salts over long distances (see Gifford and Foster, 1989). The lignins are formed by oxidative polymerisation of p-coumaryl, coniferyl and sinapyl alcohols (Freudenberg, 1965; Alder, 1977). In addition to the strengthening function of lignin it also affords the plant some protection against attack by bacterial and fungal pathogens. Lignin synthesis is often induced at the site of a pathogen attack (Vance *et al.*, 1980).

### 1.2.7, Waxes, cutin and suberin

The entire shoot system of a herbaceous plant is covered by a cuticle that prevents excessive water loss from leaves, stems, flowers, fruits and seeds (Cutler *et al.*, 1980; Juniper and Jeffree, 1982). The cuticle also provides protection against some plant pathogens, and minor mechanical damage (Kolattukudy, 1987). The cuticle is largely composed of cutin and various waxes, which are attached to the pectin polysaccharides in the cell wall. Cutin is a heterogeneous polymer made up of fatty acids (Kolattukudy, 1980). The polymeric nature of cutin arises from ester bonds uniting the fatty acid hydroxyl and carboxyl groups. Small amounts of phenolic compounds are also present in cutin, and these are thought to anchor the cutin to the pectin polysaccharide component of the cell wall via ester linkages (Holloway, 1980, Kolattukudy, 1980).

Suberin forms a protective coating over underground plant tissues, such as roots. Suberin also covers cork cells formed in tree bark by the crushing action of secondary growth, and is formed by numerous cell types as scar tissue after wounding (Kolattukudy, 1980 and 1987). Suberin forms the Casparian strip of the endodermis and exodermis, and also occurs in the bundle sheath cell walls of grasses (Kolattukudy, 1980). Suberin is made up of a complex mixture of long chain fatty acids, hydroxylated fatty acids, dicarboxylic acids, long chain alcohols, and phenolic compounds of which ferulic acid is a major component (Holloway, 1983).

### **1.2.8, Cell wall water content**

In growing plant tissues approximately two thirds of the wall mass is made up of water (Cosgrove, 1997). The bulk of this water is held within the pectin matrix, forming a dense gel (Tomos, 1988; Cosgrove, 1997). Water is a key component of the cell wall, and is apparently essential for cell wall expansion. Edelmann (1995) found that dehydration inhibits wall extension in isolated rye coleoptile cell walls. Dehydration of the wall matrix is also believed to play a direct role in growth inhibition induced by water deficits (Chazen and Neumann, 1994; Passioura, 1994). The mechanisms involved in cell expansion and cell wall extension are discussed by Cosgrove (1993) and McCann and Roberts (1994).

### **1.2.9, The hydrostatic and osmotic properties of the cell wall/apoplast**

Neutral solutes can apparently diffuse freely throughout the aqueous phase of the cell wall (Tomos, 1988). Ions and charged molecules, on the other hand, are influenced by fixed negative charges in the polymer matrix. Pectin and other macromolecules in the cell wall have a large number of carboxyl groups (-COOH) from which hydrogen ions readily dissociate. This gives the cell wall a net negative charge (Tomos, 1988, Nobel, 1991). Cations such as  $\text{Ca}^{2+}$  are electrostatically attracted to the negatively charged components of the cell wall, leading to an exchange of  $\text{H}^+$  for  $\text{Ca}^{2+}$  and other cations (see Richter and Dainty, 1989). This region of immobile negative charges in the wall is referred to as the Donnan phase (Tomos, 1988; Nobel, 1991). At equilibrium the Donnan phase attracts solutes of opposite charge from the aqueous phase of the wall,



thus creating an ion concentration gradient, which generates a Donnan potential between the Donnan phase and the bulk of the aqueous solution adjacent to it (Nobel, 1991).

The swarm of ions around the Donnan phase of the cell wall leads to a localised increase in osmotic pressure (Passioura, 1980; Tomos, 1988), which in turn draws water into the Donnan region. This influx of water generates a localised hydrostatic pressure, which is equivalent to the osmotic pressure generated by the Donnan phase (Passioura, 1980; Tomos, 1988). The countering action of the osmotic and hydrostatic forces of the Donnan phase means that the hydrostatic pressure (turgor pressure) inside adjacent cells is not affected by the Donnan phenomenon (Tomos, 1988).

Non-Donnan bound solutes present in the aqueous phase of the cell wall are osmotically active and influence the water relations of adjacent cells (Tomos, 1988). In the past it was assumed that cell wall/apoplastic solute concentrations were negligible (Tyree and Hammel, 1972; Sovonick *et al.*, 1974). However, in many plant species this has proven to be a false assumption. Glycophytes generally have relatively low concentrations of non-Donnan bound (free) solutes in the apoplast (Boyer and Knipling, 1965; Jachetta *et al.*, 1986; Nonami and Boyer, 1987). Halophytes and sink organs, on the other hand, accumulate high concentrations of osmotically active solutes in the wall (Meinzer and Moore, 1988; Flowers, 1985; Pomper and Breen, 1995; this study).

There is currently an increasing body of evidence, which suggests that cell wall solutes are actively maintained and controlled by the cell, and that they play an essential role in plant cell water relations, particularly turgor maintenance and regulation (Leigh and Tomos, 1983; Clipson *et al.*, 1985; Tomos and Wyn Jones, 1988; Tomos, 1988; Bell and Leigh, 1996).

### 1.3, Primary aim

The primary aim of the work described in this study was to establish the role of apoplastic/cell wall solutes in osmotic adjustment and turgor regulation in two members of the family *Chenopodiaceae* - the halophyte *Suaeda maritima* L. Dum. and sugar beet (*Beta vulgaris* L.). These species share a common peculiarity, in that certain cell types, namely the leaf epidermal cells in *Suaeda maritima* and the taproot storage parenchyma cells in *Beta vulgaris*, maintain a cell turgor pressure ( $P_{\text{cell}}$ ) which is dramatically lower than the respective cell osmotic pressures ( $\Pi_{\text{cell}}$ ) might suggest (see Tomos, 1988). Given the observation that the hydrostatic component of the apoplast/cell wall (the transpiration tension) does not account for these differences between  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  (Tomos, 1988), the only reasonable and sensible conclusion that can be drawn is that *Suaeda maritima* and *Beta vulgaris* accumulate and maintain a high concentration of solutes in the apoplast adjacent to these tissues, and that these free apoplastic solutes are instrumental in turgor regulation in these species.

The water relations of *Suaeda maritima* and *Beta vulgaris* were investigated at single cell resolution using a range of sophisticated and elegant techniques which are described fully in Chapter 2 (see also Tomos and Leigh, 1999). Chapters 3 through to 6 are experimental chapters, in which data are presented which highlight the remarkable properties of these species, and provide evidence which is consistent with the proposal that the apoplast can be, and is utilised as a true osmotic compartment in higher plants. In Chapter 7, the final discussion, turgor/osmotic dependent solute transport is discussed and the molecular basis of stimulus perception and osmotic adjustment (protoplastic and /or apoplastic), leading to turgor pressure regulation, is considered.



## Chapter 2 : Techniques

### 2.1, Introduction

The aim of this chapter is to introduce the single-cell techniques I employed during this research programme. The experimental chapters which follow will each have a brief method section detailing the individual experiments carried out using these techniques. Full details of equipment manufacturers and chemical suppliers are given in the **Appendix**.

### 2.2, The cell pressure probe

#### 2.2.1, Pressure probe set-up

A direct method for measuring the turgor pressure in higher plants at single cell resolution was described by Hüsken *et al.*, in 1978. The instrument consists of a fine, glass microcapillary attached by rubber seals (Cheshire Rubber Co.) to a perspex chamber, into a which a pressure transducer (Druck Ltd.) is set. The microcapillary and perspex chamber are filled with a non-viscous oil such as AS4 grade water saturated silicone oil (Wacker Chemicals Ltd.). A motor-driven metal rod (modified from a Hamilton syringe needle; Hamilton Co.) is used to increase or decrease the pressure within the oil filled system. In the pressure probe model generally used in Bangor, a solenoid valve (RS Components) is also in place designed to almost instantaneously return the oil in the probe to atmospheric pressure during single cell sampling (see **Section 2.3** and Malone *et al.*, 1989). A highly simplified plan of a pressure probe is illustrated in **Figure 2.1**; the plan is not drawn to scale.



Figure 2.1, A simplified plan of a cell pressure probe viewed from above

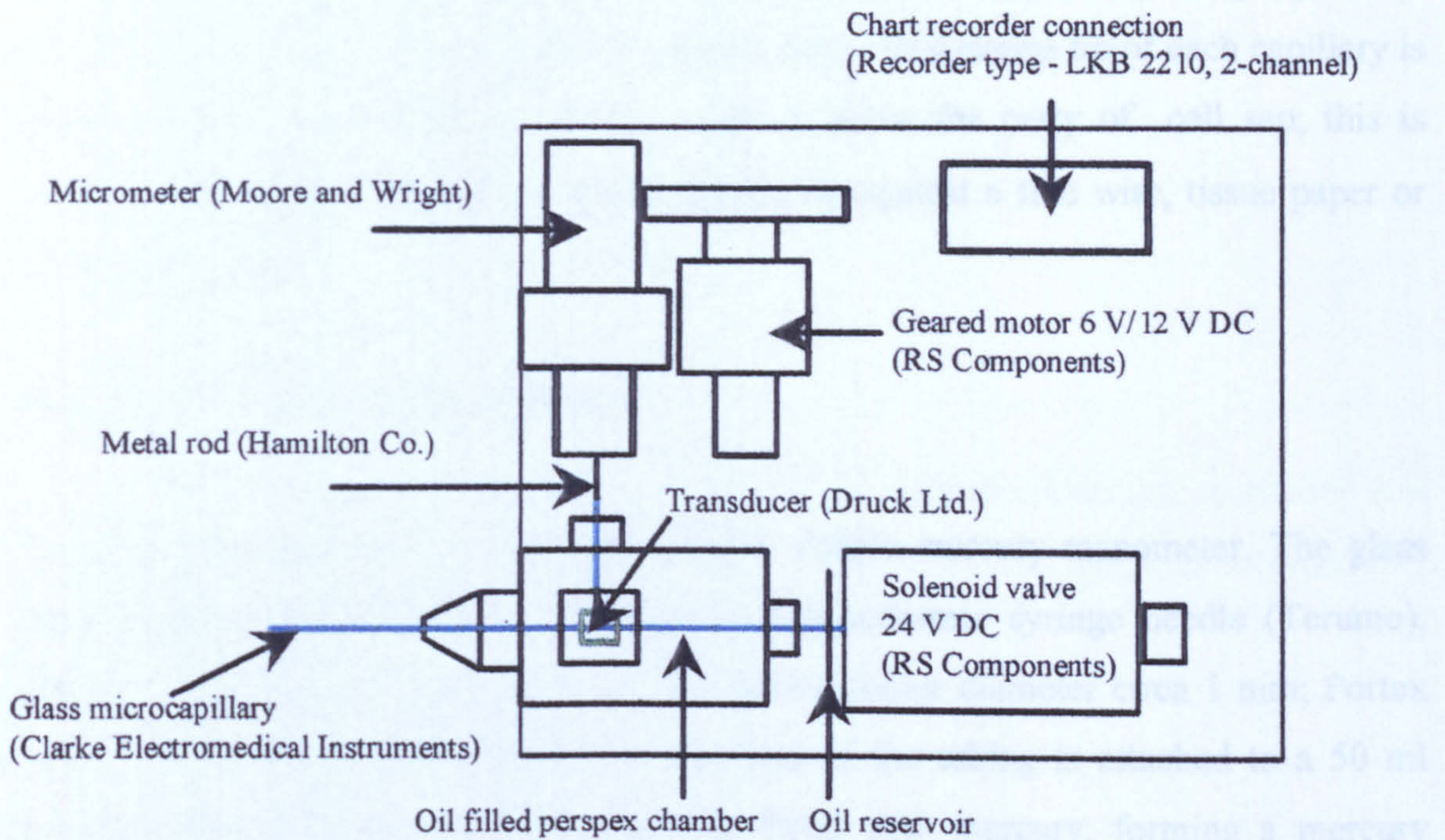
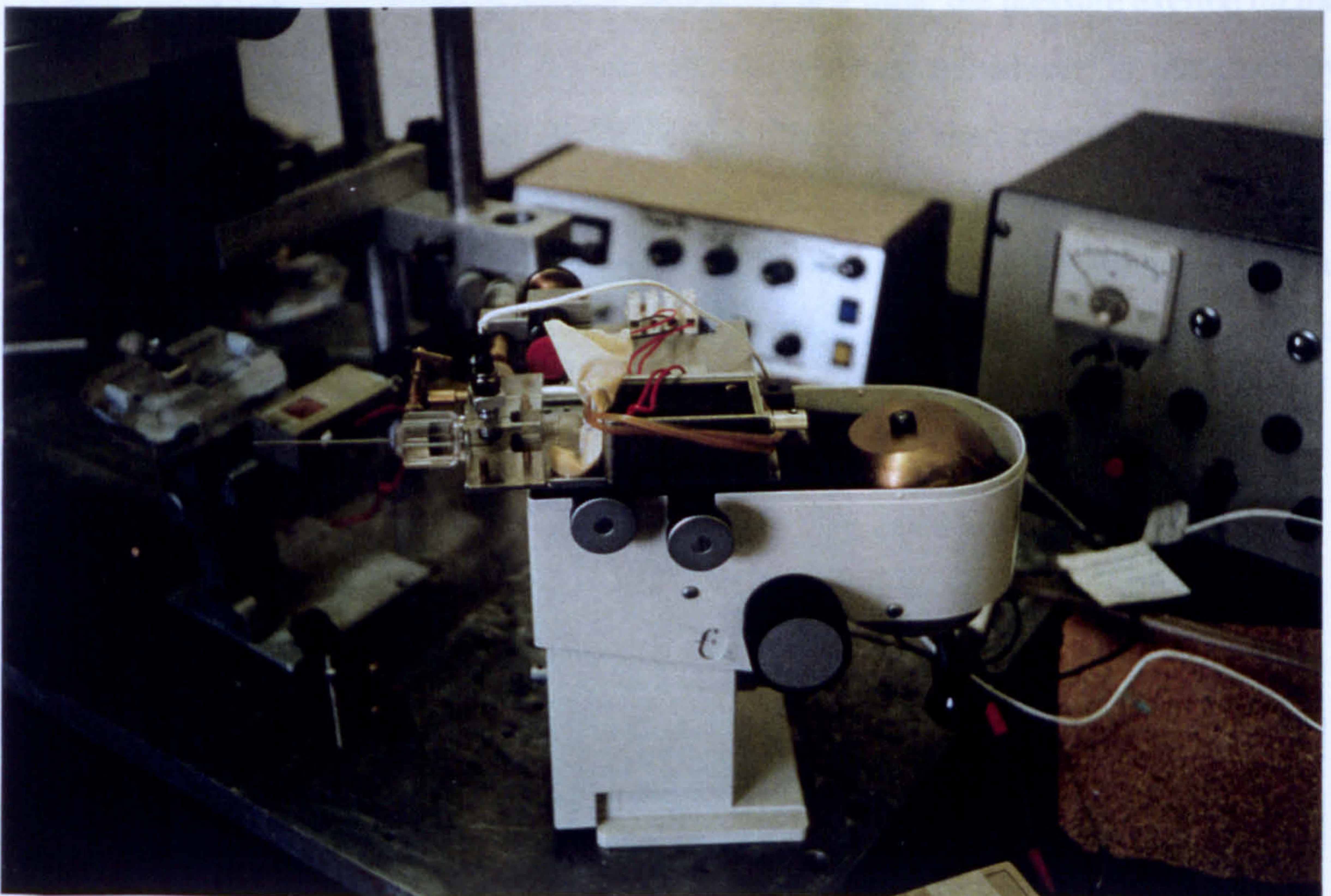


Plate 2.1, The cell pressure probe





The microcapillaries are made from 1 mm outer-diameter, 0.58 mm inner-diameter glass capillary tubing (standard wall without filament - Clark Electromedical Instruments), using a commercial capillary puller (Harvard Apparatus). Turgor pressure measurements require simple drawn out capillaries. The extreme tip of each capillary is broken slightly (to a diameter of 1 - 2  $\mu\text{m}$ ) to allow the entry of cell sap; this is achieved by gently brushing the microcapillary tip against a fine wire, tissue paper or even plant tissue.

### **2.2.2, Cell pressure probe calibration**

The cell pressure probe is calibrated using a simple mercury manometer. The glass microcapillary of the probe is replaced by a hypodermic syringe needle (Terumo), which is attached to a long length of fine tubing (outer diameter circa 1 mm; Portex Ltd.) filled with mercury (BDH). The free end of the tubing is attached to a 50 ml syringe barrel (Terumo) which is partially filled with mercury, forming a mercury reservoir. The reservoir of mercury is initially positioned level with the probe's pressure transducer (at 0 m) and then raised 1 m at a time to a height of 5 m. At a height of 0 m the pressure exerted by the mercury is 0 MPa (relative to atmospheric pressure). As the level of the mercury is raised 1 m at a time, the pressure exerted on the oil in the probe chamber, and subsequently the pressure transducer, is increased by 0.1329 MPa  $\text{m}^{-1}$ . The pressure probe is connected to a chart recorder (LKB 2210, 2-channel chart recorder) which records the output of the transducer in millivolts. Pressure in MPa is plotted against number of millivolts to give a calibration plot for that particular pressure probe transducer (see Figure 2.2). The pressure transducer is calibrated every six months, and after any probe maintenance or repair procedure.

The relationship between pressure (MPa) and the height of mercury is shown in the following equation:

$$P = \rho g h$$

$P$  = Hydrostatic pressure

$\rho$  = Density of liquid (in this case mercury)

$g$  = Acceleration due to gravity

$h$  = Depth or height of liquid

The density of mercury at 20 °C is 13550 kg m<sup>-3</sup>. The acceleration due to gravity at 0 Km altitude (sea level) is 9.81 m s<sup>-2</sup> (Halliday *et al.*, 1993). The height in this case is 1 m. Therefore:

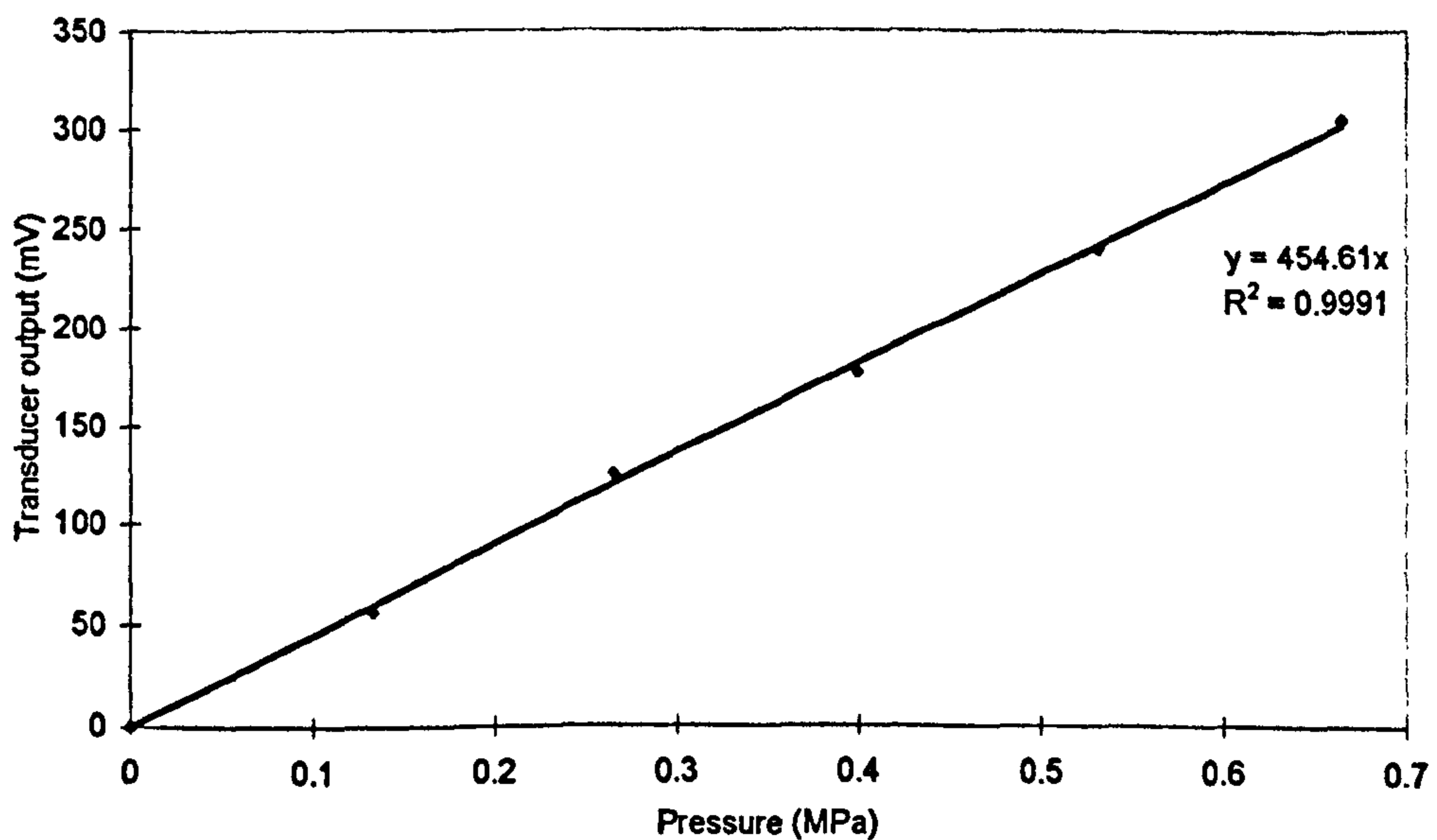
$$P = \rho g h$$

$$P = 13550 \text{ kg m}^{-3} \times 9.81 \text{ m s}^{-2} \times 1 \text{ m}$$

$$P = 132925.5 \text{ Pa}$$

$$P = 0.1329 \text{ MPa}$$

**Figure 2.2, A pressure probe transducer calibration plot**



### 2.2.3, Turgor pressure measurement

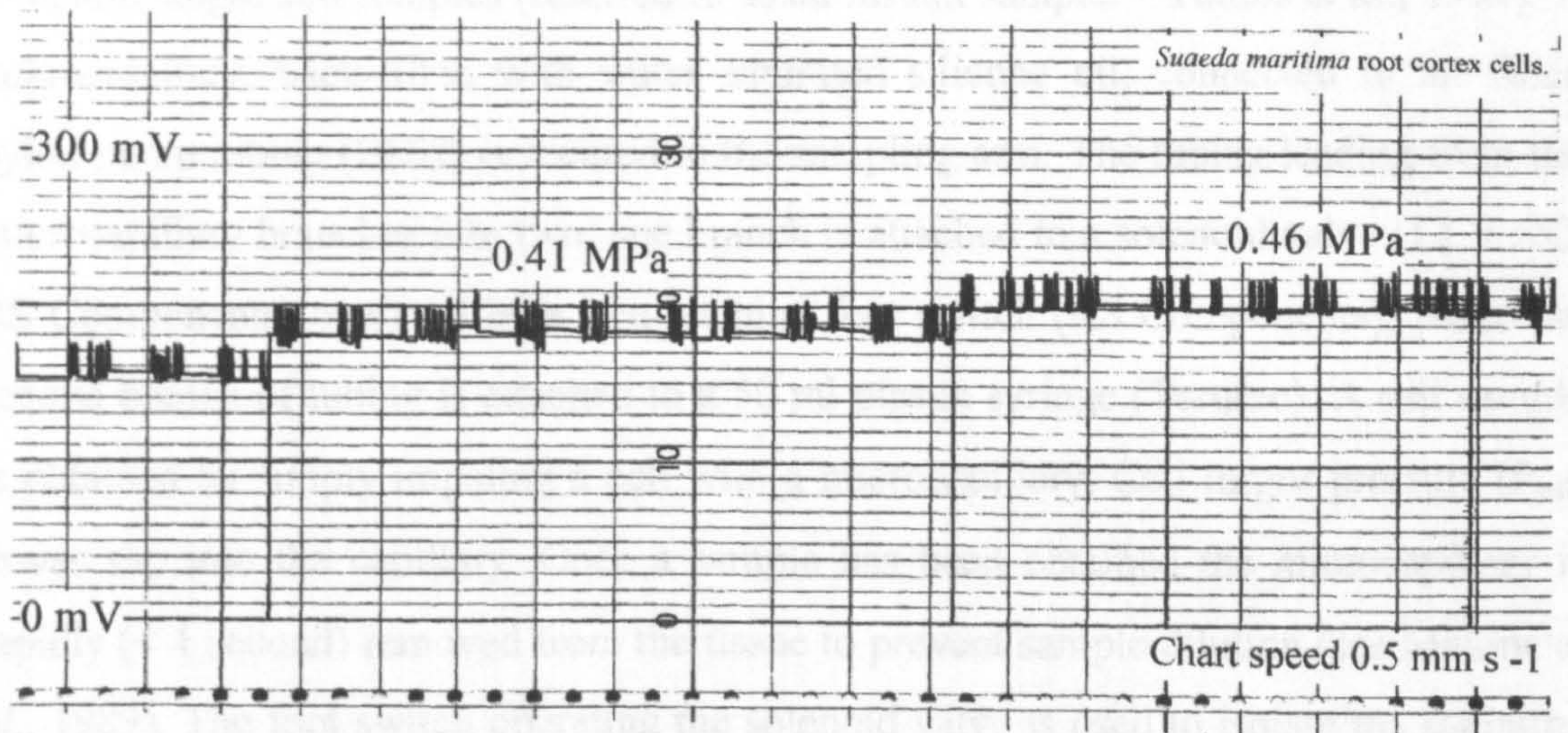
The cell pressure probe is mounted on a micromanipulator (Leitz) allowing accurate positioning and fine adjustment of the glass microcapillary. Turgor pressure measurement involves impaling a cell with a microcapillary. Sap under pressure immediately enters the capillary forming a clearly visible sap/oil interface (referred to as the meniscus). The motor-driven metal rod is used to quickly increase the pressure within the probe chamber; ideally pushing the sap back into the cell within 1 - 2 seconds. A meniscus that cannot be freely manipulated suggests that the microcapillary tip is blocked. In this situation the microcapillary is removed and replaced, and another cell is targeted. Care is taken not to introduce any air into the system during this procedure, as the compressible nature of air can cause problems when the system is pressurised. In a cell that has been successfully impaled, the sap/oil meniscus is pushed as close as possible to the cell wall. At this point the meniscus is manipulated backward and forward by modulating the pressure in the oil filled chamber using the motor-driven metal rod. The meniscus is returned to the same position each time. Providing the cell is not leaking an output pressure trace, similar to the one illustrated in **Figure 2.3**, is obtained. The output signal recorded on the chart recorder corresponds to the pressure required to push the sap back into the cell. This is equivalent to the pressure inside the cell, i.e. the cell turgor pressure ( $P_{\text{cell}}$ ). The whole procedure is viewed under a stereo microscope at maximum magnification (Wild M8, maximum magnification x 160; Leica). Depending on the application, turgor pressure measurements can be made in air (e.g. leaves) or under a liquid bathing medium (e.g. roots).

The cell pressure probe is highly sensitive to vibration. All turgor measurements are made on a vibration-resistant work bench. In Bangor the vibration-resistant benches are generally custom made using heavy concrete slabs set on breeze blocks, cushioned by cork tiles (all raw materials available from any DIY outlet). Vibration-resistant tables are available commercially from Intracel Ltd.



### Figure 2.3, A typical pressure probe output trace

Each division along the horizontal axis corresponds to 1 cm.



## 2.3, Single cell sampling

### 2.3.1, Sampling with the pressure probe

The introduction of a solenoid valve to the pressure probe set-up allows the probe to be used as a single cell sampling device (Malone *et al.*, 1989; Tomos *et al.*, 1994). Once cell turgor pressure ( $P_{\text{cell}}$ ) has been measured, a sample of cell sap can be obtained by opening the solenoid valve. This decreases the pressure inside the probe to atmospheric pressure, which allows cell sap, driven by the turgor pressure of the cell, to enter the glass microcapillary. The microcapillary, containing the sap sample, is withdrawn from the cell as quickly as possible to prevent sample dilution (the sampling procedure leads to a loss of cell turgor pressure, which in turn draws water into the cell by osmosis - see Malone *et al.*, 1989). The sap sample is expelled by closing the solenoid valve and increasing the pressure inside the probe using the motor-driven metal rod. Samples are expelled into water saturated paraffin oil (BDH) to prevent evaporation prior to analysis using a range of techniques.



### 2.3.2, Sampling with a pneumatic sampling arm

Alternatively, a simple sampling arm mounted onto the micromanipulator can be used to obtain single cell samples (referred to as an instant sampler - Tomos *et al.*, 1994). A microcapillary, back-filled with water saturated silicone oil, connected to air filled nylon pump tubing (BDH) is secured to the sampling arm. The tubing leading from the microcapillary branches into two, one branch is attached to a solenoid valve (12 V DC, RS Components) operated by a non-latching foot switch (RS Components), while the second branch of tubing is attached to a 50 ml plastic syringe (Terumo). A cell sample is obtained by simply impaling a cell with a microcapillary. Cell turgor pressure ( $P_{\text{cell}}$ ) drives sap into the capillary. Once a sample has been obtained the microcapillary is rapidly (< 1 second) removed from the tissue to prevent sample dilution (see Malone *et al.*, 1989). The foot switch operating the solenoid valve is used to isolate the sampling system from the atmosphere allowing the sample to be expelled by applying pressure to the syringe barrel.

Sampling from cells under an aqueous bathing medium (e.g. root cells) may lead to cell sap dilution/contamination due to the uptake of bathing medium into the microcapillary by capillary action (Tomos *et al.*, 1994). This is detected by observing the behaviour of the sap/oil meniscus in the microcapillary. If the meniscus moves forward (away from the plant tissue) as the microcapillary tip is withdrawn from the cell, the sample is discarded. To combat this problem, the microcapillaries are silanized prior to use.

### 2.3.3, Microcapillary silanization

Microcapillaries are placed tip upwards in an aluminium capillary holder in a glass Pyrex beaker. The beaker is covered with aluminium foil and placed in a 200 °C oven for a minimum of 2 hours. The microcapillaries must be completely dry before silanization and are usually left in the oven overnight. The silanization procedure simply involves injecting 50  $\mu\text{l}$  dimethyl-dichlorosilane (Sigma Chemicals) through the foil with a pipette and returning the microcapillaries to the oven for a further 2 hours.

The silane evaporates and coats each microcapillary, forming a hydrophobic surface. Dimethyl-dichlorosilane vapour is harmful; the silanization procedure is carried out in a fume cabinet and strict COSHH regulations are adhered to at all times. Silanized microcapillaries can be stored indefinitely.

## **2.4, Manipulation of single cell samples**

### **2.4.1, Sample storage and manipulation**

Single cell samples can be stored successfully for several days, or even longer, sandwiched between oil in a microcapillary at 4 °C (Tomos *et al.* 1994). However, I preferred to prepare and analyse each sample within 4 hours of sampling.

Individual single cell samples are expelled into water saturated paraffin oil to prevent evaporation. The paraffin oil is contained within an aluminium ring (custom made) which has been glued onto a microscope slide with epoxy resin adhesive. Each ring-slide is thoroughly cleaned and dried before use. The ring is washed in 10% Decon 90 (Decon Laboratories Ltd.) and hot water, and then rinsed in ethanol (BDH) and de-ionised water before being dried in a 200 °C oven for 30 minutes. The ring-slide is filled with water saturated paraffin oil and placed on an adjustable stage (Prior Scientific Instruments), under the stereo microscope. Single cell samples obtained as described in Section 2.3.1 and 2.3.2, are expelled into the oil and form small droplets on the glass slide. From here each droplet of cell sap can be sub-sampled and prepared for analysis.

### **2.4.2, Constriction microcapillaries**

Sub-samples of equal volume can be taken using constriction pipettes (Tomos *et al.*, 1994). Microcapillaries are prepared using a commercial capillary tip puller as described in Section 2.2.1. The capillary tip is constricted using a commercial microforge (Beaudouin, Paris). The barrel of the microcapillary is carefully positioned alongside a heated wire micro-element using the microforge controls and microscope. A



constriction is formed as the microcapillary tip is drawn closer to the heated micro-element. Care is taken not to make the constriction too narrow as this will restrict the flow of sap into the capillary. Constriction pipettes of different volumes can be made by varying the diameter of the capillary barrel and/or by constricting the microcapillary further away from the tip (Lowry and Passonneau, 1972; Tomos *et al.*, 1994). The constriction pipettes used in my experiments were all approximately 10  $\mu$ l in volume.

### 2.4.3, Sub-sample manipulation

The constriction microcapillaries are attached to a sampling arm mounted on the micromanipulator, as described in Section 2.3.2. Samples are drawn up into the microcapillary by closing the solenoid valve and creating a vacuum in the syringe. As the sample reaches the mid-point of the constriction, the solenoid valve is released and the sample ceases to enter the microcapillary. Sub-samples of equal volume can be drawn up using the same constriction microcapillary pipette. Silanization of the constriction microcapillaries is not essential but often makes the sample easier to manipulate within the pipette. Up to five sub-samples can be drawn into the same microcapillary, each sample sandwiched between a volume of water saturated paraffin oil. The sub-samples can then be expelled by closing the solenoid valve and pressurising the syringe.

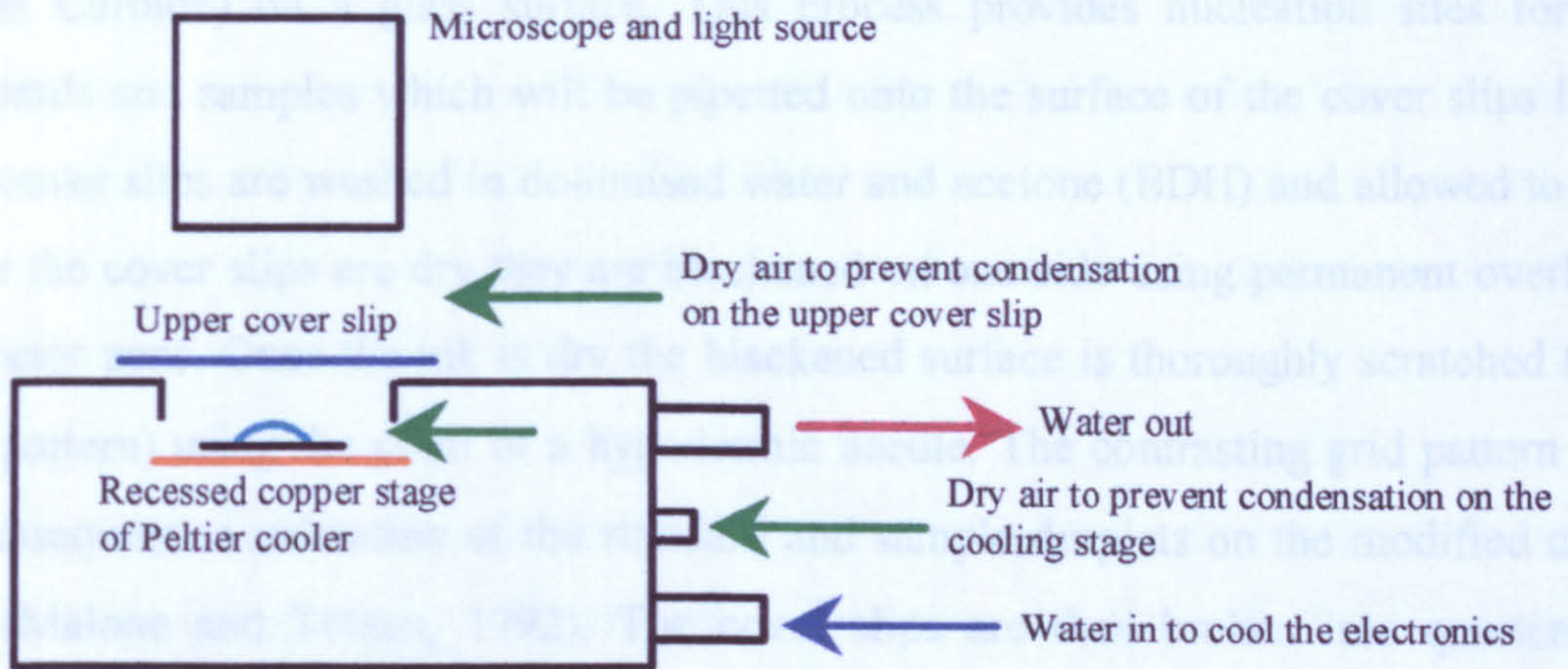
## 2.5, Picolitre osmometry

### 2.5.1, Osmometer set-up

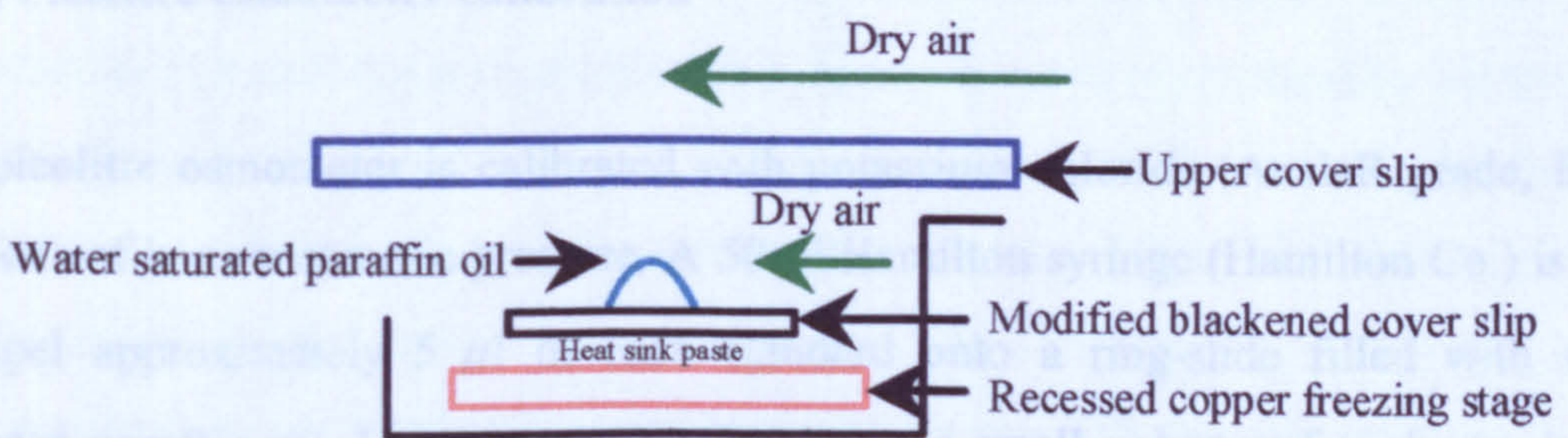
The osmotic pressure ( $\Pi_{\text{cell}}$ ) of single cell samples is determined by measuring melting-point depression using a custom built picolitre osmometer (Malone *et al.*, 1989; Tomos *et al.*, 1994). A simplified diagram of a typical Bangor-built picolitre osmometer is illustrated in Figure 2.4 {a} and {b}. A pea size amount of white heat sink compound (RS Components) is placed in the middle of the recessed, copper stage.



**Figure 2.4 {a}, A picolitre osmometer cooling unit (not drawn to scale)**



**Figure 2.4 {b}, The recessed copper cooling stage (not drawn to scale)**





Using forceps (curved tip N° 7; Agaraid), a modified blackened cover slip is positioned on top of the heat sink compound and gently pressed into place (Figure 2.4 {b}). The modified cover slips are prepared in the following way: Large cover slips (22 mm) are abraded on both sides in a slurry of abrasive alumina powder (Buehler Micropolish, Union Carbide) on a glass surface. This process provides nucleation sites for the standards and samples which will be pipetted onto the surface of the cover slips later. The cover slips are washed in de-ionised water and acetone (BDH) and allowed to dry. Once the cover slips are dry they are blackened on one side using permanent overhead projector pens. Once the ink is dry the blackened surface is thoroughly scratched (in a grid pattern) using the point of a hypodermic needle. The contrasting grid pattern aids in subsequent visualisation of the standard and sample droplets on the modified cover slip (Malone and Tomos, 1992). The cover slips are then broken into quarters by pressing down evenly with a sharp single-edged razor blade (TAAB Laboratory Equipment Ltd.). The unblackened surface is carefully cleaned with a lens tissue (Whatman International Ltd.) and ethanol before use. The cover slips are positioned blackened surface down onto the heat sink compound. Once in place, a small droplet of water-saturated paraffin oil is expelled onto the centre of the cover slip using a syringe. Standards and samples are pipetted onto the cover slip, within the droplet of oil, using the pneumatic sampling arm (Section 2.3.2) and appropriate microcapillary.

### **2.5.2, Picolitre osmometer calibration**

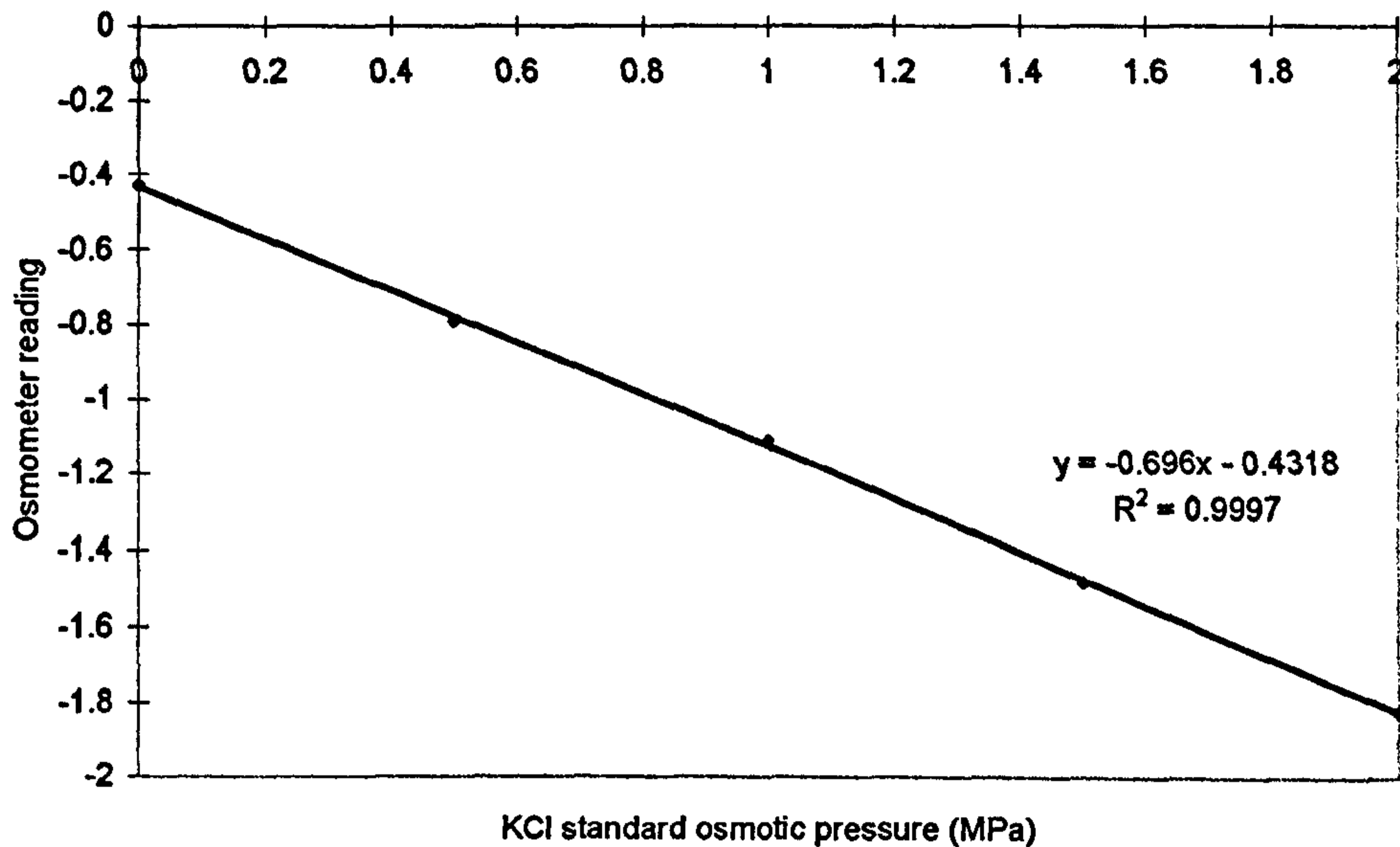
The picolitre osmometer is calibrated with potassium chloride (AnalaR grade, BDH) solutions of known osmotic pressure. A 50  $\mu\text{l}$  Hamilton syringe (Hamilton Co.) is used to expel approximately 5  $\mu\text{l}$  of each standard onto a ring-slide filled with water saturated paraffin oil. Using a stereo microscope a small volume of each standard is picked up using the pneumatic sampling arm and a constriction microcapillary pipette (see Section 2.3.2 and 2.4.2). As noted earlier, up to five standards can be drawn into the pipette, each sandwiched between a volume of paraffin oil. Once the standards are safely contained within the pipette they are expelled onto the modified cover slip on the osmometer stage.

During the osmometer freezing cycle the Peltier cooler is cooled to - 40 °C to overcome the effects of super cooling and facilitate droplet freezing (Tomos *et al.*, 1994), before stabilising at around -5 °C. This freezing cycle generates a lot of heat. The osmometer is kept cool by continuously cycling water through the apparatus via tubing connected to a 15 °C water bath (Haake D3 Circulator; Fisher Scientific). A simple connection to the cold water mains supply is also adequate. Condensation is minimised by covering the recessed copper stage with a cover slip and by using a dry air supply. Air passed over silica gel crystals (BDH) is channelled beneath and/or above the upper cover slip using tubing and a three way tap system.

The osmometer hand set is used to initiate the freezing cycle. At this stage the dry air supply is passed both above and below the upper cover slip. Once the freezing cycle has begun the osmometer temperature control is turned to the coldest setting. The osmometer stage is cooled to - 40 °C, to induce freezing of the tiny droplets, rising to - 5 °C at the end of the cycle (each freezing cycle takes about 2 minutes). The frozen droplets should be clearly visible against the black and white background of the modified cover slip. The lower dry air supply is often switched off at this point as the upper air supply is generally adequate to eliminate condensation, providing that the upper cover slip is not removed. The temperature of the osmometer stage is then slowly increased until the ice crystals within the droplets begin to melt. The reading on the osmometer hand-set is recorded at the point where the ice crystals disappear. This procedure is repeated for each droplet. A calibration curve is obtained by plotting the osmometer reading against the known osmotic pressure of each standard (the standard droplets are positioned amongst the sap sample droplets). **Figure 2.5** shows a typical osmometer calibration curve. It is good practice to calibrate the osmometer at the beginning and at the end of an experiment to counter any drift that may occur.



**Figure 2.5, A typical picolitre osmometer calibration plot**



### 2.5.3, Measuring osmotic pressure in single cell samples

Samples can be placed on the osmometer stage directly from the cell, or smaller sub-samples can be taken from the ring-slide using the sampling arm and a constriction microcapillary, as described in Section 2.4.3. Droplets are placed on the osmometer stage while the osmometer is set at the warmest temperature setting. Whenever the upper cover slip is removed, dry air is channelled across the osmometer stage to prevent condensation forming on the surface of the oil. The freezing procedure for sample droplets is the same as described for the KCl standards (see Section 2.5.2). Once osmotic pressure has been measured the samples can be drawn back up into a microcapillary pipette and used for further analysis.

## **2.6, Energy dispersive X-ray microanalysis (EDX)**

### **2.6.1, Protocol outline**

Elements bombarded with high energy electrons emit X-rays with element specific characteristics. These can be used to quantify the amount of an element present in a sample (Morgan, 1985; Hinde, 1994; Tomos *et al.* 1994; Hinde *et al.*, 1998).

Standards and samples of fixed volume (typically 10  $\mu$ l) are pipetted onto a thin 100/200-mesh copper grid (Agaraid) covered with a fine membrane of Pioloform (see Hinde, 1994; Hinde *et al.*, 1998). Each standard and sample droplet contains an equal volume of internal standard (250 mM rubidium nitrate in saturated mannitol; Sigma Chemicals and BDH respectively). The droplets are dried and analysed using a scanning electron microscope (Tomos *et al.* 1994). The resulting energy spectrum is used to calculate the concentration of elements in a sample.

### **2.6.2, Pipetting standards and samples onto a copper grid**

Pioloform coated 200/100-mesh, folding copper grids are prepared as described by Hinde (1994). Pre-coated grids are also available commercially from Agaraid. A coated copper grid is positioned at the centre of a ring-slide, containing water saturated paraffin oil, Pioloform face up. Using curved forceps (N° 7; Agaraid), the grid is carefully lowered into the oil at a 45° angle, to prevent air being trapped beneath the membrane, and then gently positioned on the glass slide. A small volume (approximately 5  $\mu$ l) of each standard (EDX standard composition is shown in Table 2.1), including the rubidium/mannitol internal standard, is expelled onto the ring slide, around the copper grid, using a 50  $\mu$ l Hamilton syringe. The pneumatic sampling arm and a 10  $\mu$ l silanized constriction pipette is used to pick up five sub-samples of each standard (see Section 2.3.2 and 2.4.3). The standards are then pipetted onto the Pioloform membrane. Each droplet is placed on the centre of a grid square, on the 200-mesh side of the copper grid. Using the same constriction pipette an identical volume of internal standard (RbNO<sub>3</sub>/mannitol) is added to each standard droplet on the



grid. The rubidium concentration chosen is preferably equivalent to that of the major element expected in the sample. Inclusion of a rubidium internal standard allows the data to be normalised against the rubidium signal. The mannitol provides a matrix in which the elements are evenly dispersed as the sample droplet boils under the electron beam (Malone *et al.* 1991; Hinde, 1994; Tomos *et al.* 1994; Cuin, 1996, Bates, 1998; Hinde *et al.*, 1998).

Single cell samples, taken directly from the cell or from the osmometer stage, can be expelled initially onto the ring slide or onto the 100-mesh side of the copper grid. From here sub-samples are taken and pipetted onto the 200-mesh grid as described above. Care must be taken to include an equal volume of RbNO<sub>3</sub>/mannitol internal standard to each sample droplet. Pipetting samples onto a grid is often a lengthy process, in order to limit evaporation from the sample and standard droplets the picolitre osmometer unit is used to cool the ring slide to approximately 4 °C. The position of each droplet pipetted on to the copper grid is noted on a grid map to aid in sample/standard identification later.

**Table 2.1, EDX standard element composition and concentration**

<b>Standard</b>	<b>Na<sup>+</sup> (mM)</b>	<b>Cl<sup>-</sup> (mM)</b>	<b>K<sup>+</sup> (mM)</b>	<b>Ca<sup>2+</sup> (mM)</b>
<b>1</b>	0	0	0	0
<b>2</b>	100	100	100	50
<b>3</b>	200	200	200	100
<b>4</b>	300	300	300	150
<b>5</b>	400	400	400	400

All standards were made up from the following AnalaR salts: sodium chloride, potassium nitrate and calcium nitrate (BDH).

### 2.6.3, Drying standard and sample droplets

The droplets are dried onto the grid in the following way: The copper grid is lifted out of the water saturated paraffin oil using curved forceps. Care is taken to avoid the 200-mesh side of the grid. The grid is dipped in a vial of water saturated hexane (Rathburn Chemicals) and gently rotated for 30 seconds to remove the paraffin oil. The grid is then transferred to a second vial of hexane and the procedure is repeated. Finally the grid is washed in a vial of water saturated isopentane (BDH) for a further 30 seconds before being allowed to dry in ambient air for a few seconds. The entire drying procedure is carried out in a fume cabinet (see Hinde, 1994; Tomos *et al.* 1994; Bates, 1998). The grids can be stored indefinitely in small plastic capsules (Agaraid) over silica gel crystals in a sealed container at room temperature.

### 2.6.4, X-ray microanalysis

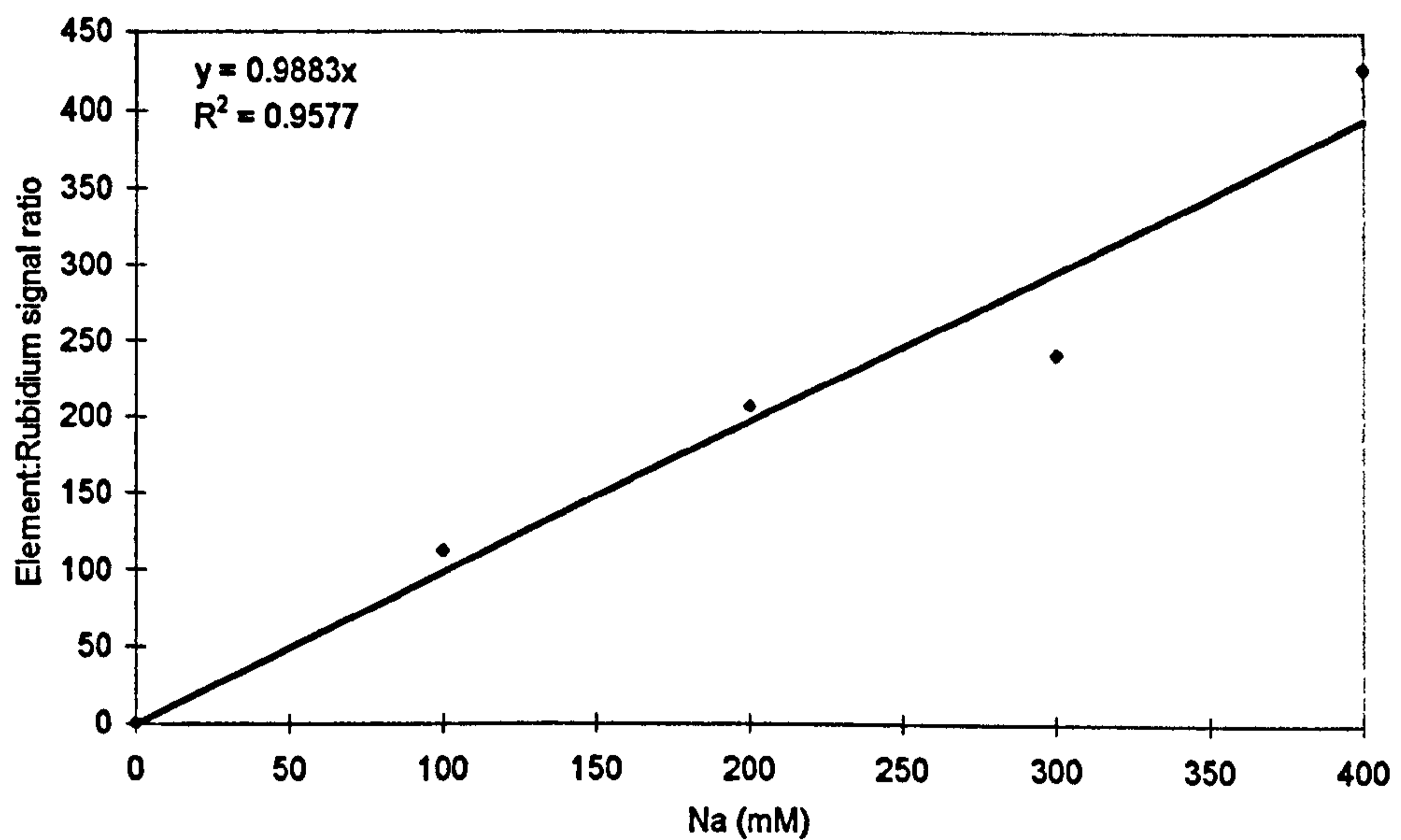
X-ray analysis is carried out using a scanning electron microscope (Hitachi S520) equipped with a Si-Li detector coupled to a Link Analytical QX2000 microanalytical system. The 100-mesh side of the grid is secured to a modified carbon block by a fine gauge sprung brass clip. The carbon block is then mounted on an aluminium stub, which in turn is positioned inside the scanning electron microscope chamber. The sample is aligned at a 45° angle to the detector and electron gun. Once a vacuum has been established in the sample chamber the dried microdroplets are individually scanned with an electron raster just large enough to cover the droplet. Analysis continues until the gross integral for rubidium has reached 4500 counts or 1000 seconds has elapsed (whichever is sooner). The accelerating voltage is set at 14 kV (Hinde, 1994; Bates, 1998; Hinde *et al.*, 1998). When  $K^+$  and  $Ca^{2+}$  are present in the same sample the signal peaks overlap. To counter this, 10 % of the  $K^+$  signal is subtracted from the  $Ca^{2+}$  signal (Tomos *et al.*, 1994; Hinde *et al.*, 1998).



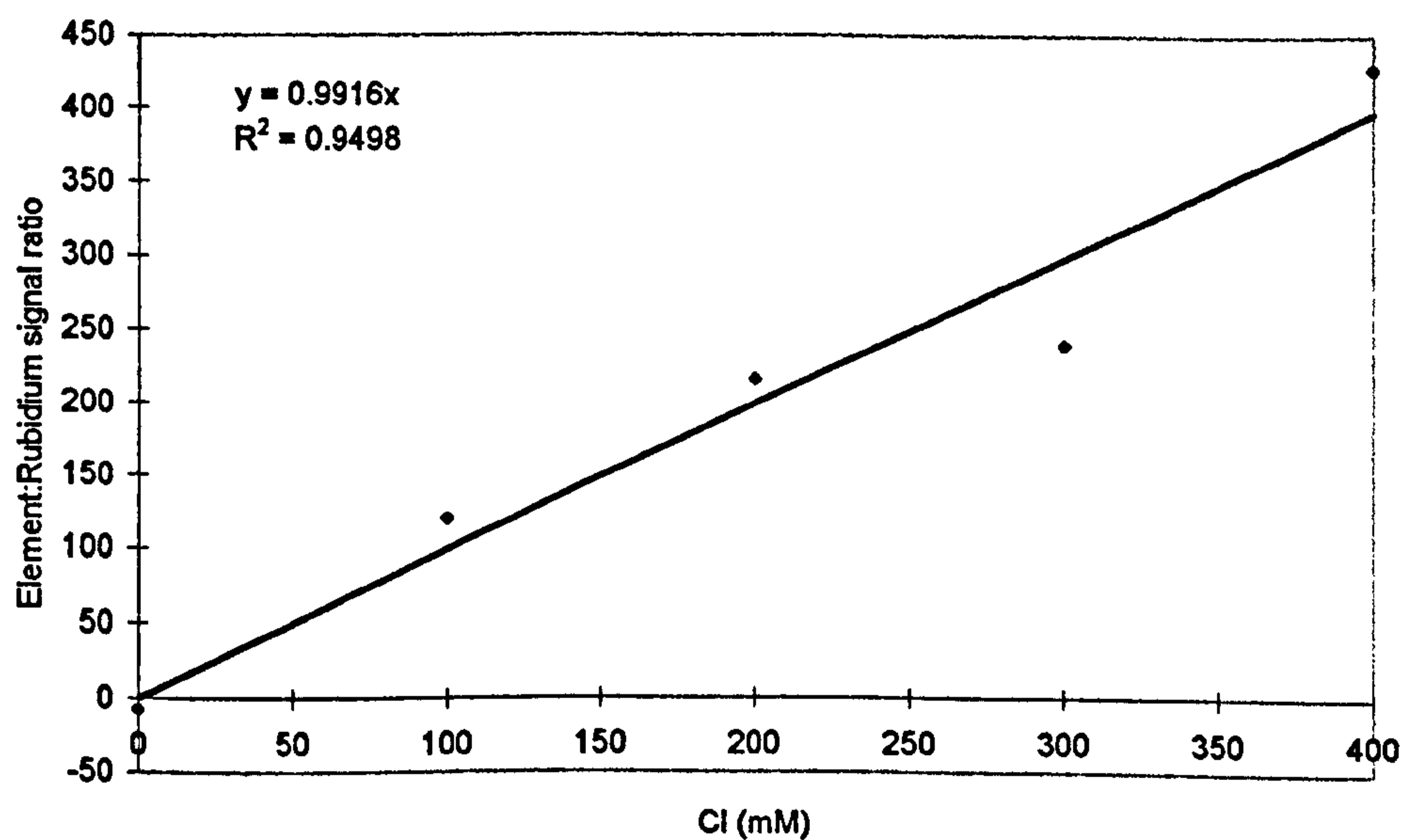
The element:rubidium signal ratio is calculated for each element. The signal ratio is then plotted against the known concentration of the element in the standard droplets to give a calibration plot (see Figure 2.6 {a to d}).

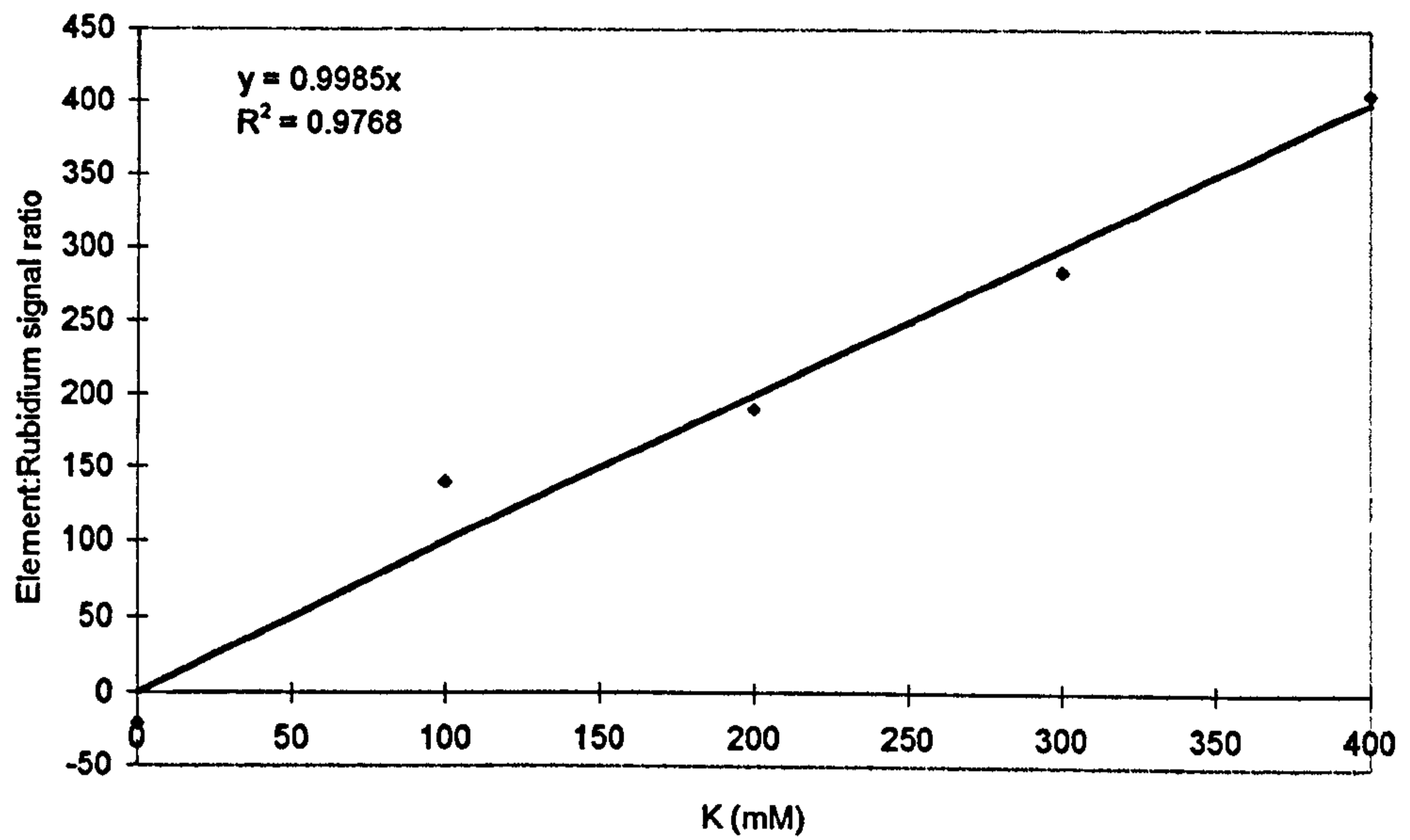
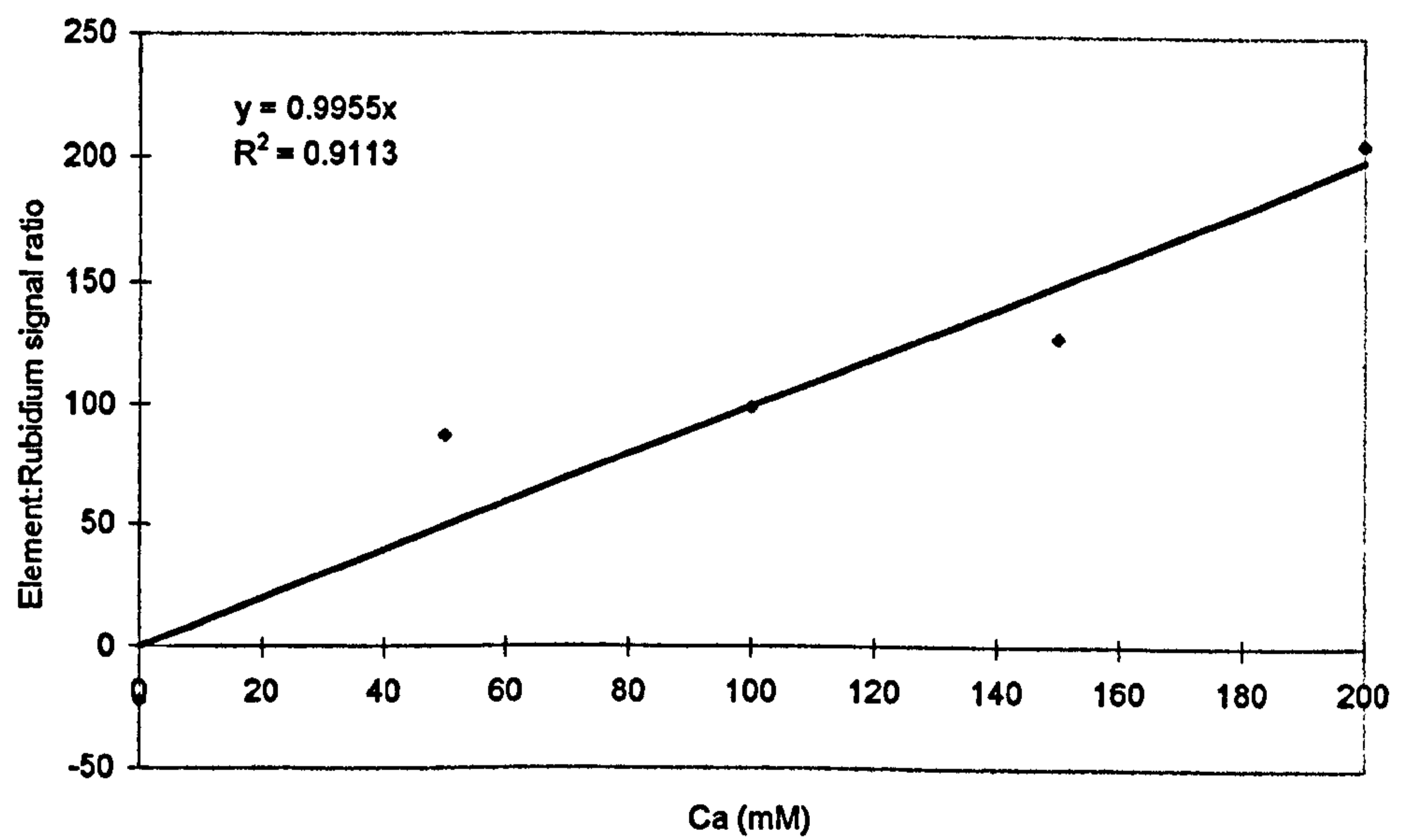
Figure 2.6, A typical EDX calibration plot

{a} Sodium



{b} Chloride



**{c} Potassium****{d} Calcium**



## 2.7, The xylem pressure probe

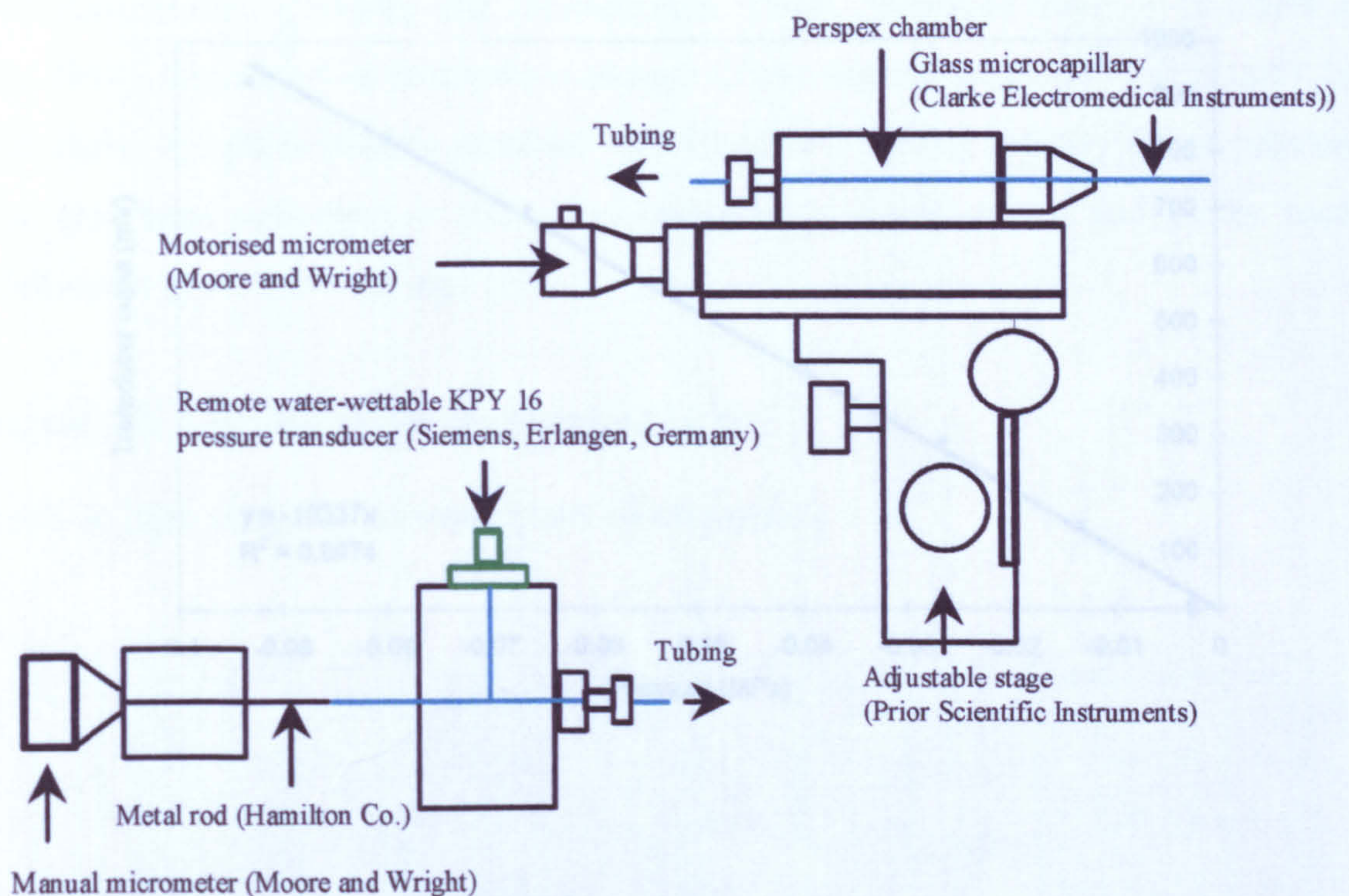
### 2.7.1, Xylem probe set-up

Balling and Zimmermann (1990) described a direct method for measuring xylem tension/pressure ( $P_{\text{xylem}}$ ) in the xylem vessels of an intact plant. The xylem pressure probe has evolved from the cell pressure probe described in Section 2.2. The instrument consists of a fine glass microcapillary connected by rubber seals to a perspex chamber, which is attached to a remote water-wettable KPY 16 pressure transducer (Siemens, Erlangen, Germany) via fine tubing. The microcapillary and perspex chamber, through to the remote pressure transducer, are filled with degassed, de-ionised water rather than silicone oil. Water is substituted for oil in this system, as cavitation most readily occurs at the oil/sap interface during a xylem pressure measurement (Balling *et al.*, 1988; Balling and Zimmermann, 1990). The microcapillaries are made from capillary tubing, using a commercial capillary puller (as described for the cell pressure probe in Section 2.2.1). The extreme tip of each microcapillary is broken to a diameter of approximately  $5 \mu\text{m}$ . The pressure inside the xylem probe system can be modulated using a manually-driven metal rod (Hamilton Co.), which is fed through rubber seals into the xylem probe chamber. The probe is mounted on a motorised micrometer (Moore and Wright) on a fully adjustable stage (Prior Scientific Instruments). A simplified plan of the xylem pressure probe is illustrated in Figure 2.7 (not drawn to scale).

The xylem pressure probe is connected to a control panel which drives the motorised micrometer, which in turn allows the microcapillary to travel in and out of the plant tissue. The control panel also allows a motor cut off point to be set manually. When the xylem probe pressure transducer detects a pressure which is equivalent to or greater than that of the predetermined cut off point, the motor stops automatically. This is an essential xylem probe feature, as the probe operator cannot see the tip of the microcapillary (once it has entered the tissue) or the targeted xylem vessel. The motor cut off point is generally set between  $-0.0025 \text{ MPa}$  and  $-0.005 \text{ MPa}$  (relative to atmospheric pressure).



**Figure 2.7, A simplified side view of a xylem pressure probe**

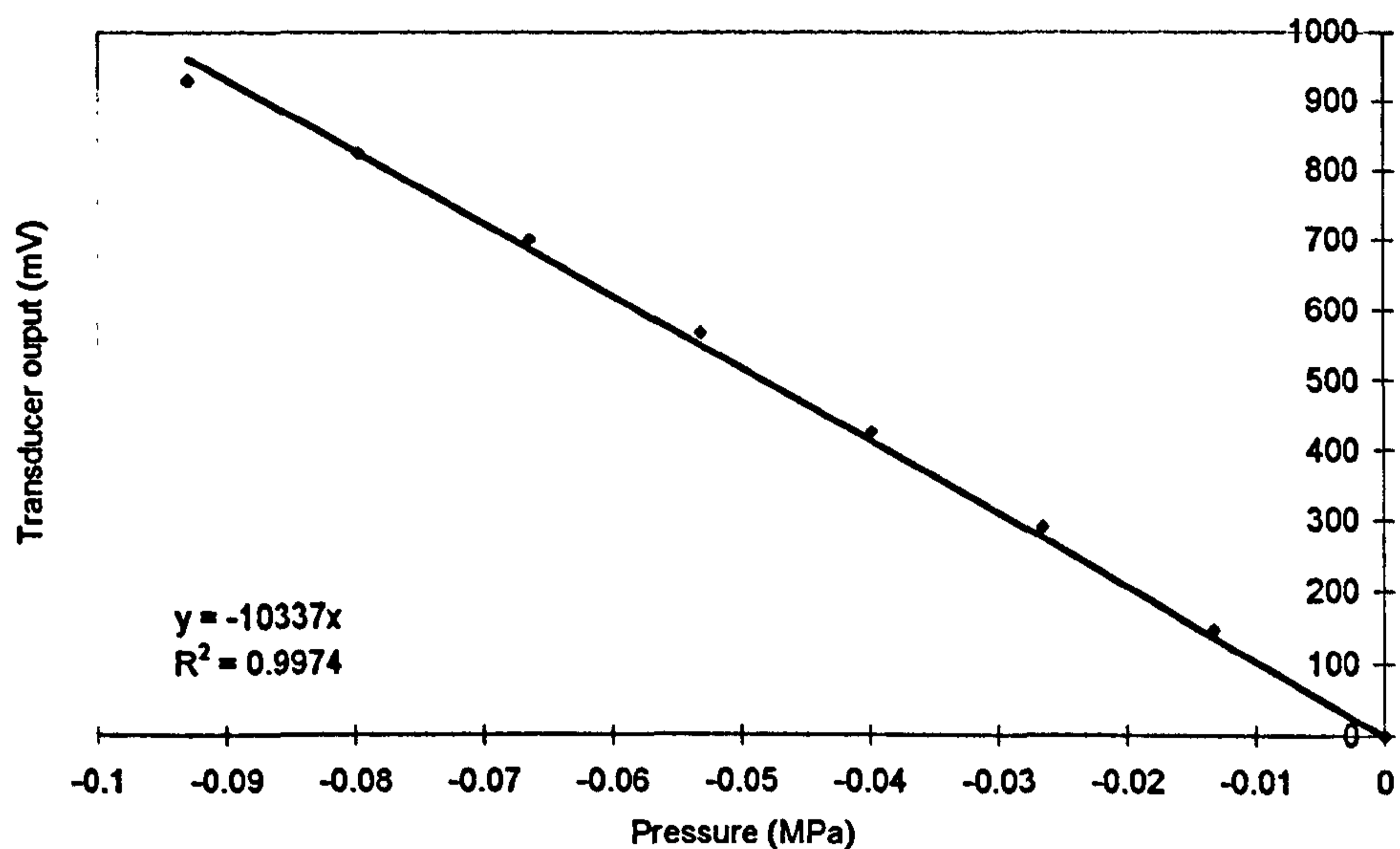


### 2.7.2, Xylem pressure probe calibration

The xylem pressure probe is calibrated using a mercury manometer (as described for the cell pressure probe in **Section 2.2.2**). The xylem probe and pressure transducer are raised to a height of 1 m (from the floor) on a vibration-resistant work bench. The reservoir of mercury is initially positioned level with the pressure transducer to register 0 MPa (relative to atmospheric pressure). The mercury is then lowered, at 10 cm intervals, towards the floor. A 10 cm decrease in the level of the mercury reservoir results in a 0.01329 MPa decrease in the pressure exerted on the pressure transducer. The relationship between pressure (MPa) and height of mercury is explained in **Section 2.2.2**. The xylem probe is connected to a chart recorder which records the output of the pressure transducer in mV. A calibration curve is obtained by plotting pressure in MPa against number of millivolts (**Figure 2.8**).



**Figure 2.8, A typical xylem probe transducer calibration plot**



### 2.7.3, Xylem pressure measurement

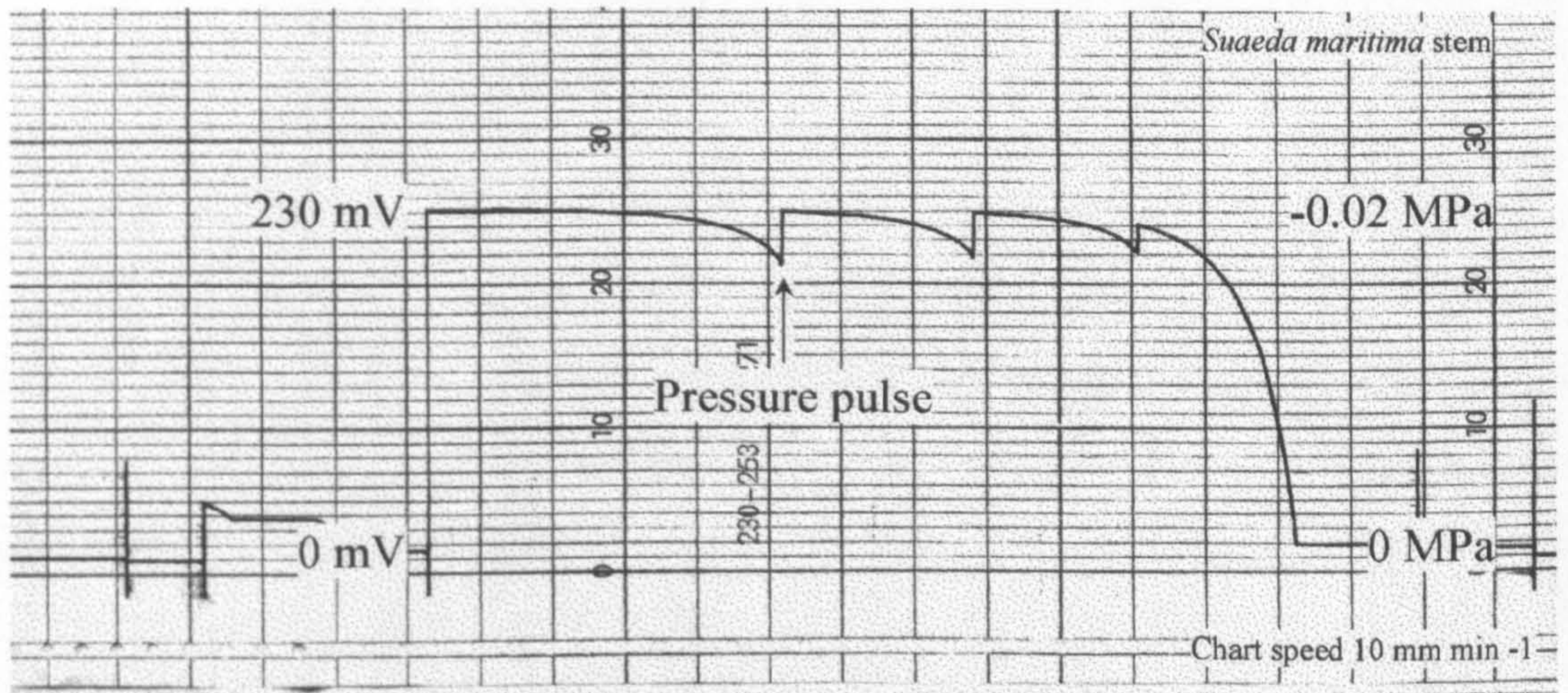
The xylem pressure probe microcapillary is positioned adjacent to the area of stem to be probed using the adjustable stage; positioning is by eye only. The motorised micrometer advances the glass microcapillary through stem. Penetration stops immediately when the pressure transducer registers a pressure equivalent to or greater than the predetermined cut off point set on the control panel. Pressure pulses are introduced into the system using the manually driven metal rod; pressure recovery indicates that the microcapillary tip is not blocked. Providing the xylem pressure probe and plant are not disturbed in any way, xylem pressure can be measured successfully for an hour or more. A xylem probe output trace is shown in Figure 2.9. Unfortunately, the microcapillary tip often fails to hit a xylem vessel at all. In this situation the microcapillary is withdrawn from the tissue and a different section of stem is targeted. If the microcapillary is blocked (i.e. water cannot be freely expelled from the tip by increasing the pressure in the xylem probe chamber using the metal rod) or broken, it is replaced, taking care not to introduce any air into the probe chamber during the



procedure. Successful xylem pressure measurement requires patience and perseverance. Successful xylem pressure measurements have been obtained from the stems of *Nicotiana rustica* ((Balling and Zimmermann, 1990), *Nicotiana tabacum* (Benkert *et al.*, 1991), the mangrove *Rhizophora mangle* (Zimmermann *et al.*, 1994 {b}), and the salt marsh halophyte *Suaeda maritima* (see **Chapter 3**). More recently xylem pressure has also been measured in roots, for example, in maize, wheat and barley roots (Schneider *et al.*, 1997 {a} and {b}).

### Figure 2.9, A typical xylem probe output trace

Each division along the horizontal axis corresponds to 1 cm.





## 2.8, Summary

<b>Parameter</b>	<b>Technique</b>	<b>Section</b>
Turgor pressure ( $P_{\text{cell}}$ )	Cell Pressure Probe	2.2
Osmotic pressure ( $\Pi_{\text{cell}}$ )	Picolitre Osmometry	2.5
Inorganic ions	EDX analysis	2.6
Xylem pressure ( $P_{\text{xylem}}$ )	Xylem pressure probe	2.7

## Chapter 3 : Salt tolerance in *Suaeda maritima* L. Dum.

### 3.1, Introduction

*Suaeda maritima* (L.) Dum. is a remarkable halophyte which has been widely used in physiological studies of the mechanism of salt tolerance in halophytes (Flowers, 1975; Flowers *et al.*, 1977; Greenway and Munns, 1983; Yeo, 1983; Clipson, 1987). *Suaeda maritima* can tolerate a wide range of NaCl concentrations, and grows optimally at 200 mM NaCl (Yeo, 1974; Flowers *et al.*, 1977; Yeo and Flowers, 1980). This species also grows successfully in the absence of NaCl (Flowers, 1971; Clipson, 1987; this chapter), however, its distribution is confined to saline areas due to the pressures of competition in the glycophytic domain (Chapman, 1947; Clapham *et al.*, 1962; Clapham *et al.*, 1987).

Using the sophisticated suite of single cell techniques introduced in Chapter 2, the salt tolerance mechanisms employed by *Suaeda maritima* (in steady state and fluctuating external NaCl) can be studied at single cell resolution. In this study the hydrostatic and osmotic properties of leaf epidermal cells and root cortex cells were determined using the cell pressure probe ( Husken *et al.*, 1978; Tomos, 1988; Chapter 2, Section 2.2), picolitre osmometry (Chapter 2, Section 2.5) and EDX analysis (Tomos *et al.*, 1994; Chapter 2, Section 2.6). The hydrostatic nature of the xylem, located in the stem, was determined using the xylem pressure probe (Balling *et al.*, 1988; Balling and Zimmermann, 1990; Chapter 2, Section 2.7).

#### 3.1.1, *Suaeda maritima* (L.) Dum.

*Suaeda maritima* belongs to the family *Chenopodiaceae*. This family is made up of about 100 genera containing at least 500 plant species (Clapham *et al.*, 1962; Clapham *et al.*, 1987). A characteristic feature of the *Chenopodiaceae* is the tolerance of its members to adverse conditions such as drought and salinity (McArthur and Sanderson, 1984); approximately half of the genera within the family include examples of halophytes (Flowers and Yeo, 1988).



The genus *Suaeda* is made up of about 40 species, consisting mainly of herbs and small shrubs. Members of this genus have a cosmopolitan distribution and are generally found in saline habitats (Clapham *et al.*, 1987).

The species *Suaeda maritima* is an annual dicot which is native to the British Isles, occurring exclusively on salt marshes and sea shores usually below the high water mark of spring tides (Chapman, 1947). This species is also common around the coasts of Europe (except the Arctic), and is found inland in saline areas of Central Europe, Russia, Eastern Asia, the East Indies and North America. Subspecies, or possibly other closely related allied species, have also been found in South America and Australia (Chapman, 1947; Clapham *et al.*, 1962 and 1987).

The Flora of the British Isles recognises three varieties of *Suaeda maritima* (L.) Dum. (Clapham *et al.*, 1962 and 1987). A brief description follows below:

- *Var. maritima* (also referred to as *Var. vulgaris* Moq. by Chapman, 1947). Plant large, branches spreading. Seed not more than 1.5 mm in diameter. Flowers August to October.
- *Var. macrocarpa* (Desv.) Moq. Plant decumbent or prostrate, rarely erect and then small. Leaves up to 10 mm, seed 2 mm in diameter. Flowers July to August.
- *Var. flexilis* (Focke.) Rouy. Usually erect, often unbranched and never branched from the base; branches are short and erect. Leaves 10 - 25 mm. Seed 1.1 - 1.4 mm in diameter. Flowers August to October.

The *Suaeda maritima* variety described in this chapter is *var. maritima*. Seeds were collected from a local salt marsh, near Brynsiencyn, on the Isle of Anglesey, North Wales. Further details regarding the site location and collection of seeds are included in the following methods section (Section 3.2).

### 3.1.2, Structure and anatomy

A simple line drawing of *Suaeda maritima* is presented in **Figure 3.1**. The cell types targeted along the axis of the plant, throughout this salt tolerance study, are illustrated in the following photomicrographs and accompanying labelled cell plans. The magnitude of magnification (indicated above each photomicrograph) refers only to the photomicrograph and not to the cell plan.

*Suaeda maritima* leaves emerge in pairs. Initially each leaf pair forms a discernible tier along a central axis. After 3 or 4 leaf pairs have emerged axillary leaves and subsequently branches develop sequentially up the axis. For ease of identification each leaf pair can be allocated an appropriate number or symbol. A transverse section through a typical *Suaeda maritima* leaf approaching full expansion is illustrated in **Photomicrograph 3.1**. The leaves are cylindrical and succulent in nature. The leaf is protected by a single layer of epidermal cells which are characteristically uniform adaxially and abaxially. Pressure probe and sampling work was carried out on epidermal cells situated mainly on the adaxial surface of the leaf. This cell type was chosen due to uniformity of the tissue and ease of access.

The photosynthetic parenchyma cells adjacent to the adaxial epidermis resemble elongated palisade cells, whereas the photosynthetic parenchyma adjacent to the abaxial leaf surface are rounded and spongy in nature. Towards the centre of the leaf the parenchyma cells become enlarged and irregular; these cells are referred to as water cells. The xylem and phloem tissue are arranged in vascular bundles. A large vascular bundle is positioned centrally with smaller bundles radiating away towards the extremes of the leaf.

*Suaeda maritima* has an extremely fine and delicate root system. A transverse section through a root, approximately 1 cm from the root tip, is illustrated in **Photomicrograph 3.2**. The outer layer of cells form the protective epidermis. Directly beneath the epidermis are three layers of large cortical cells. The root cortex is not tightly packed and has numerous air spaces. Specialised, thickened cortical cells, referred to as the endodermis encircle the vascular tissue. The vascular tissue is positioned in the centre

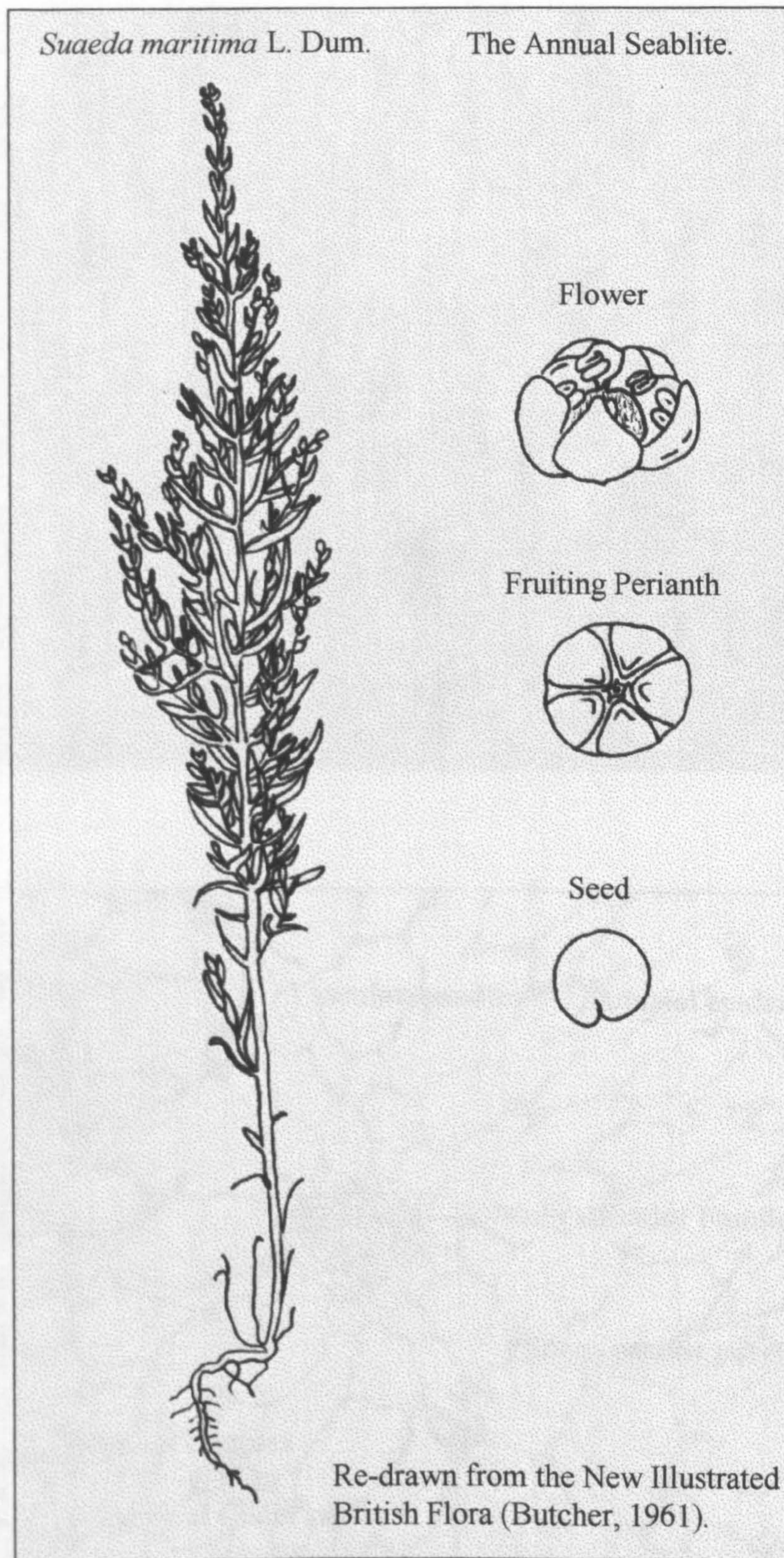


of the root, and consists of an outer pericycle and inner xylem and phloem tissue. The root tissue targeted for probing and sampling purposes was the large root cortex.

The stem (particularly below the cotyledons) is often a quite complex structure (Mauseth, 1988). Xylem pressure probe measurements were taken midway between the root and cotyledon. The structure of the stem in this region is illustrated in **Photomicrograph 3.3**. This photomicrograph beautifully illustrates how the xylem and phloem tissues are scattered almost at random throughout this tissue. The xylem vessel cells are large and numerous, which is ideal for xylem pressure probe work. The stem consists of an outer epidermis (which appears to be breaking away from the main body of tissue in this example), followed by a ring of uniform cortical cells. Below the cortex lies a more thickened tissue, referred to as sclerenchyma tissue. Embedded within the this thickened tissue are the vascular tissues. The thickened sclerenchyma and vascular tissues form a large central core within the stem.

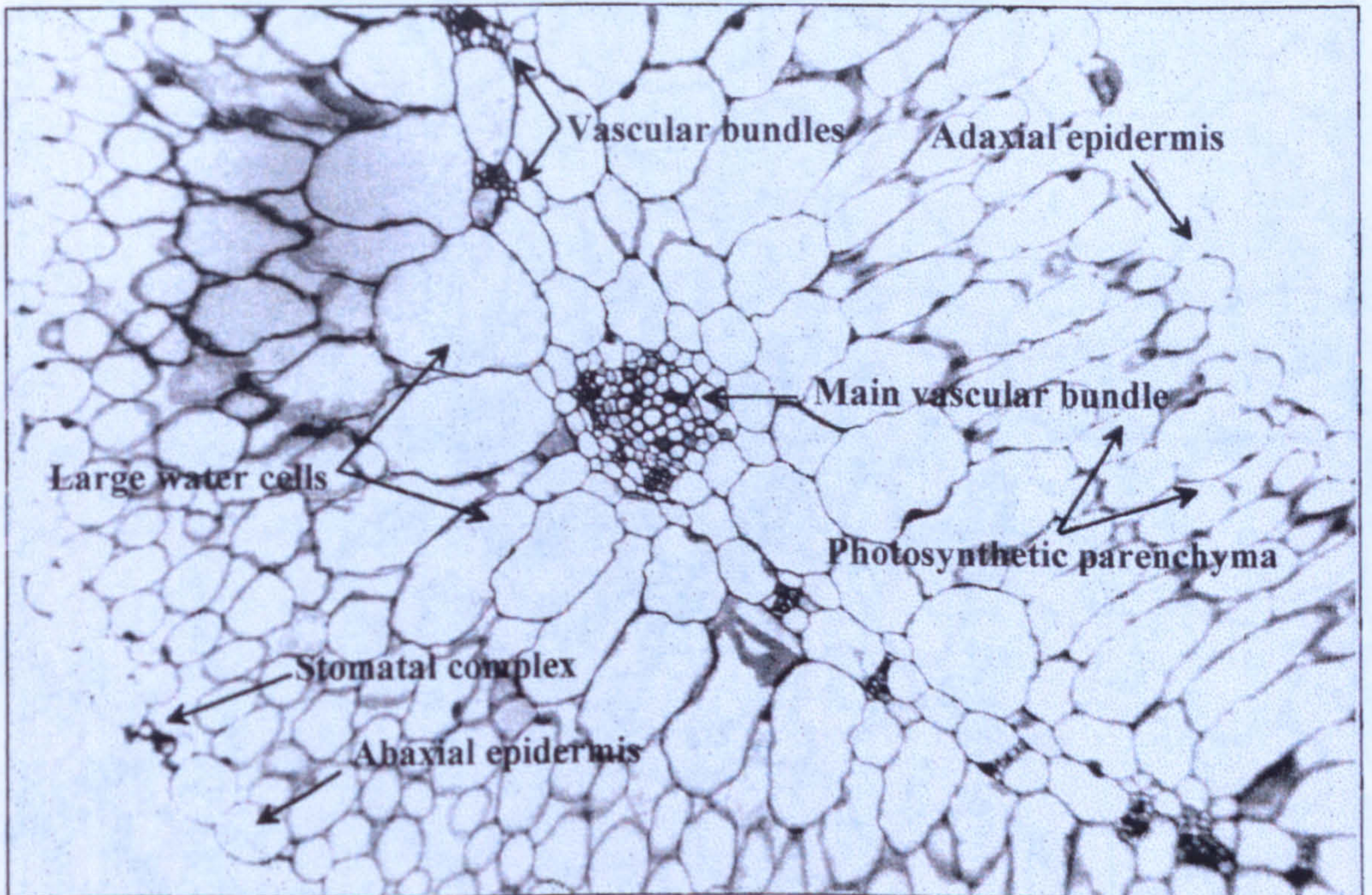
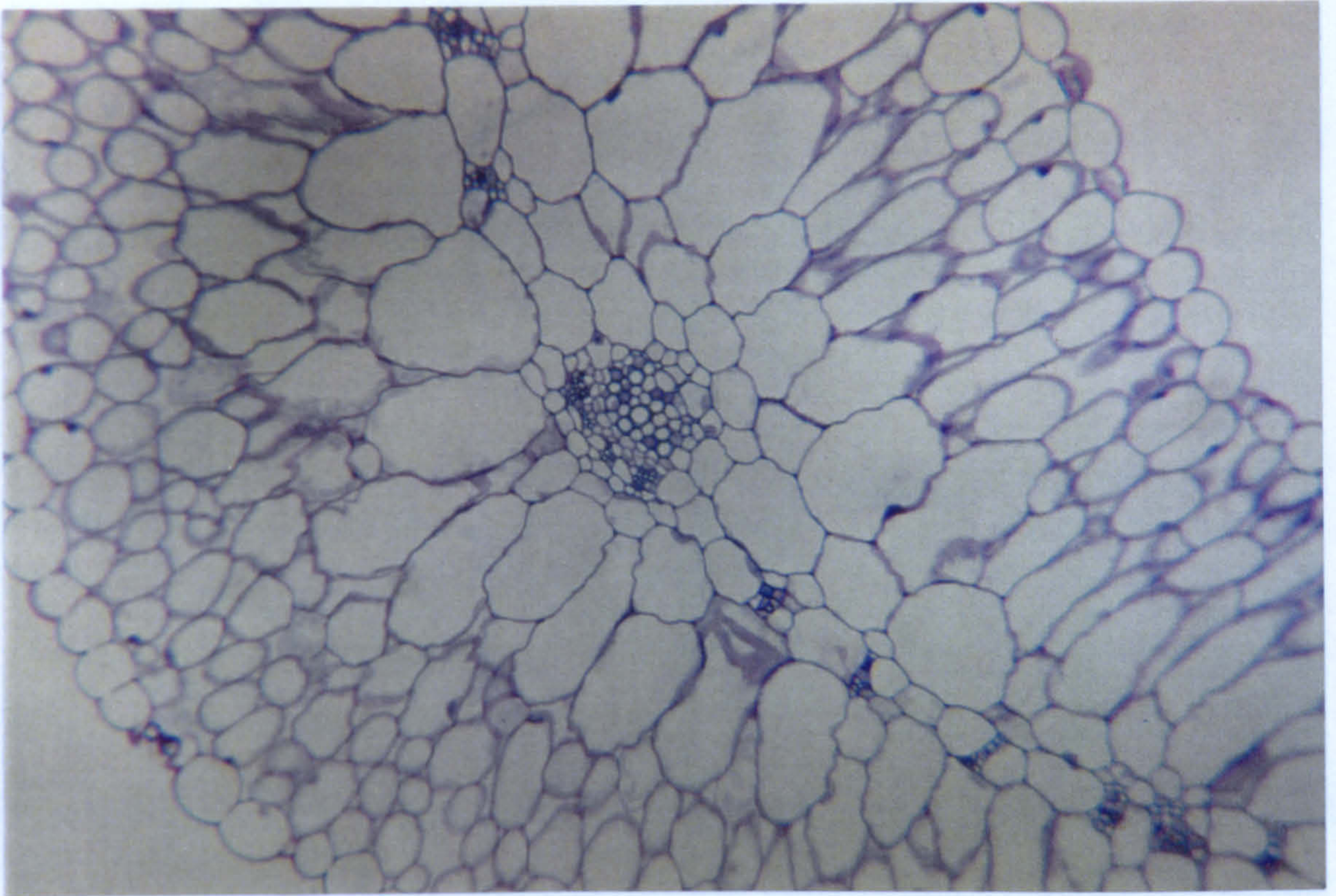


Figure 3.1, *Suaeda maritima* line drawing



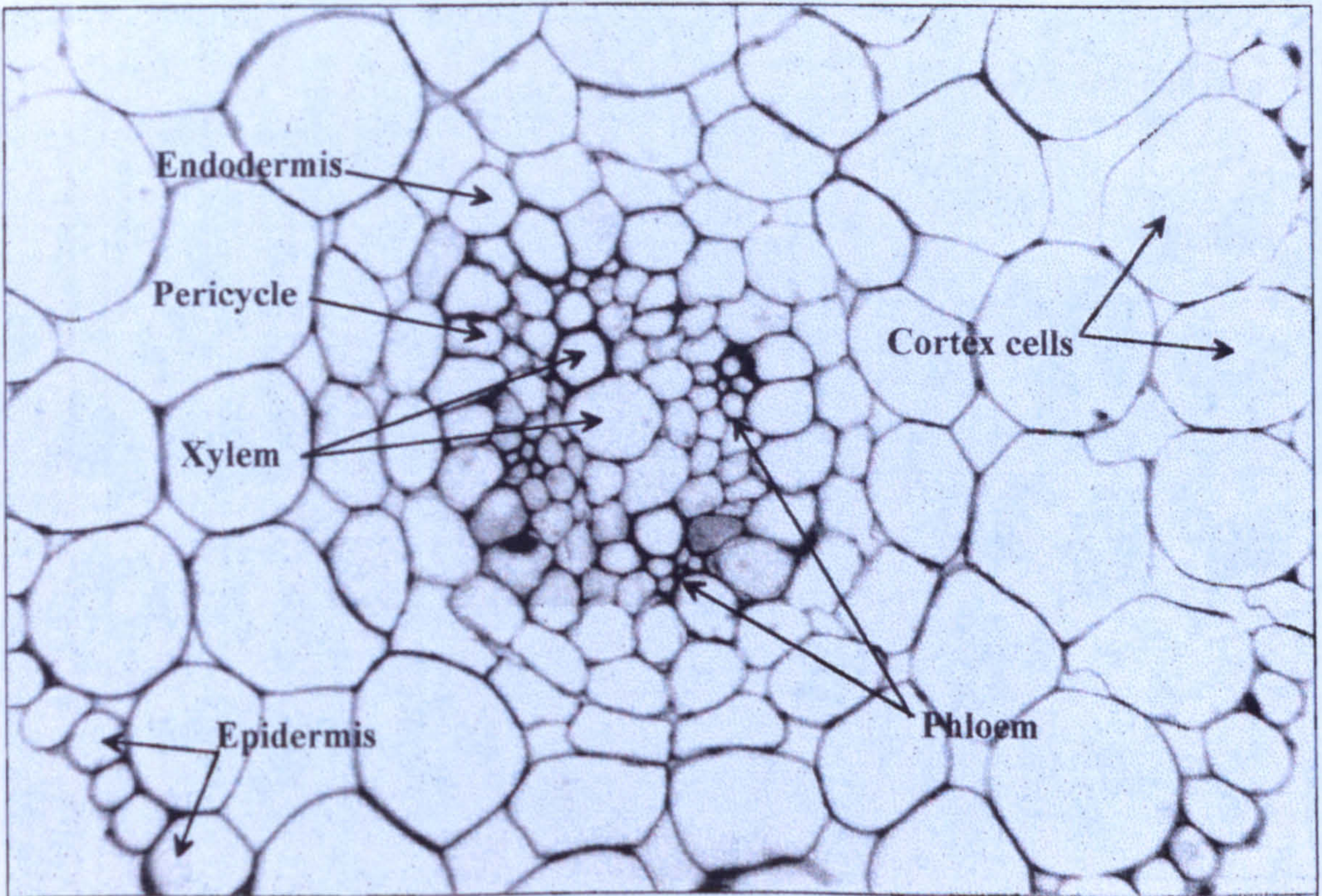
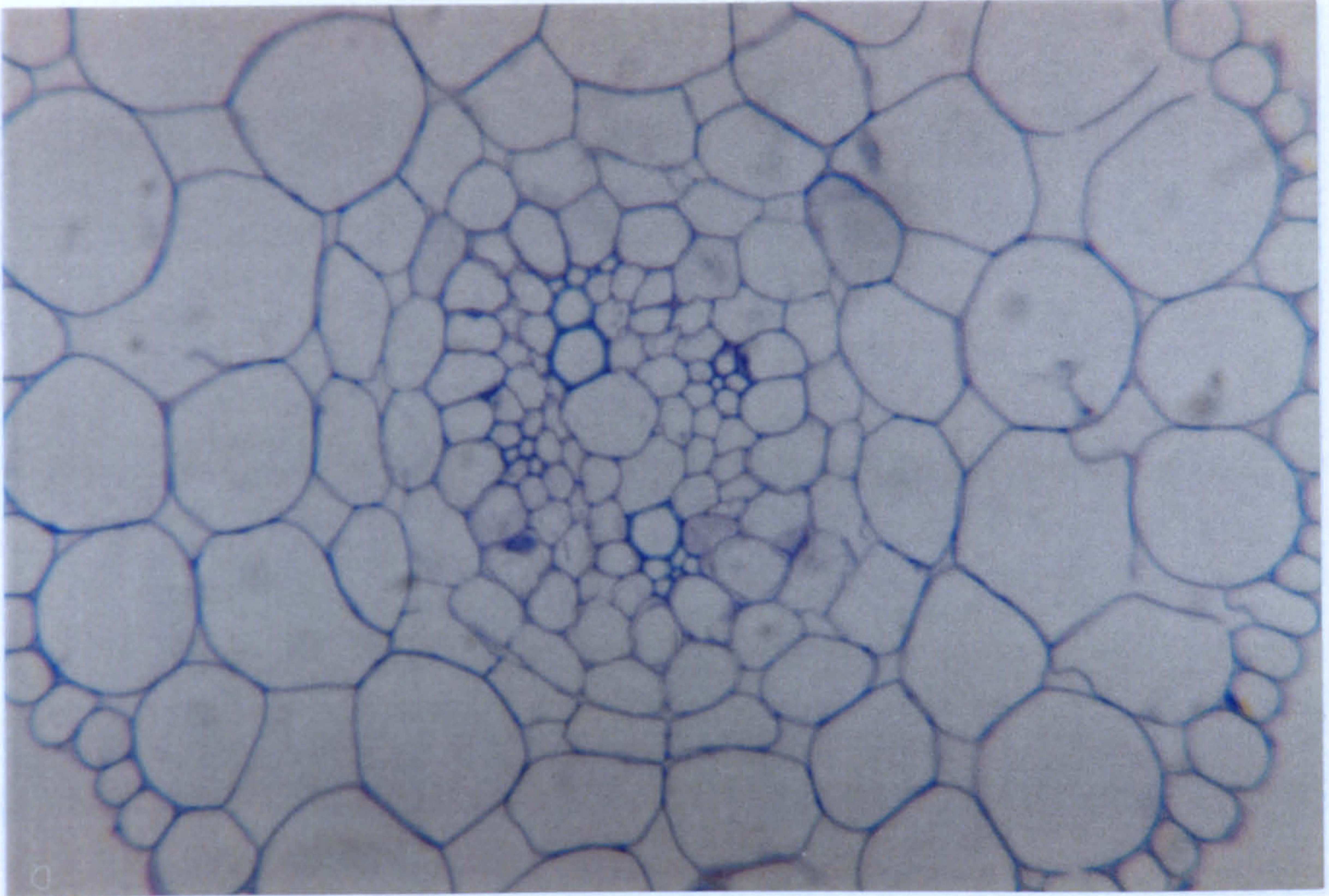


Photomicrograph 3.1, TS *Suaeda maritima* leaf ( x 100)



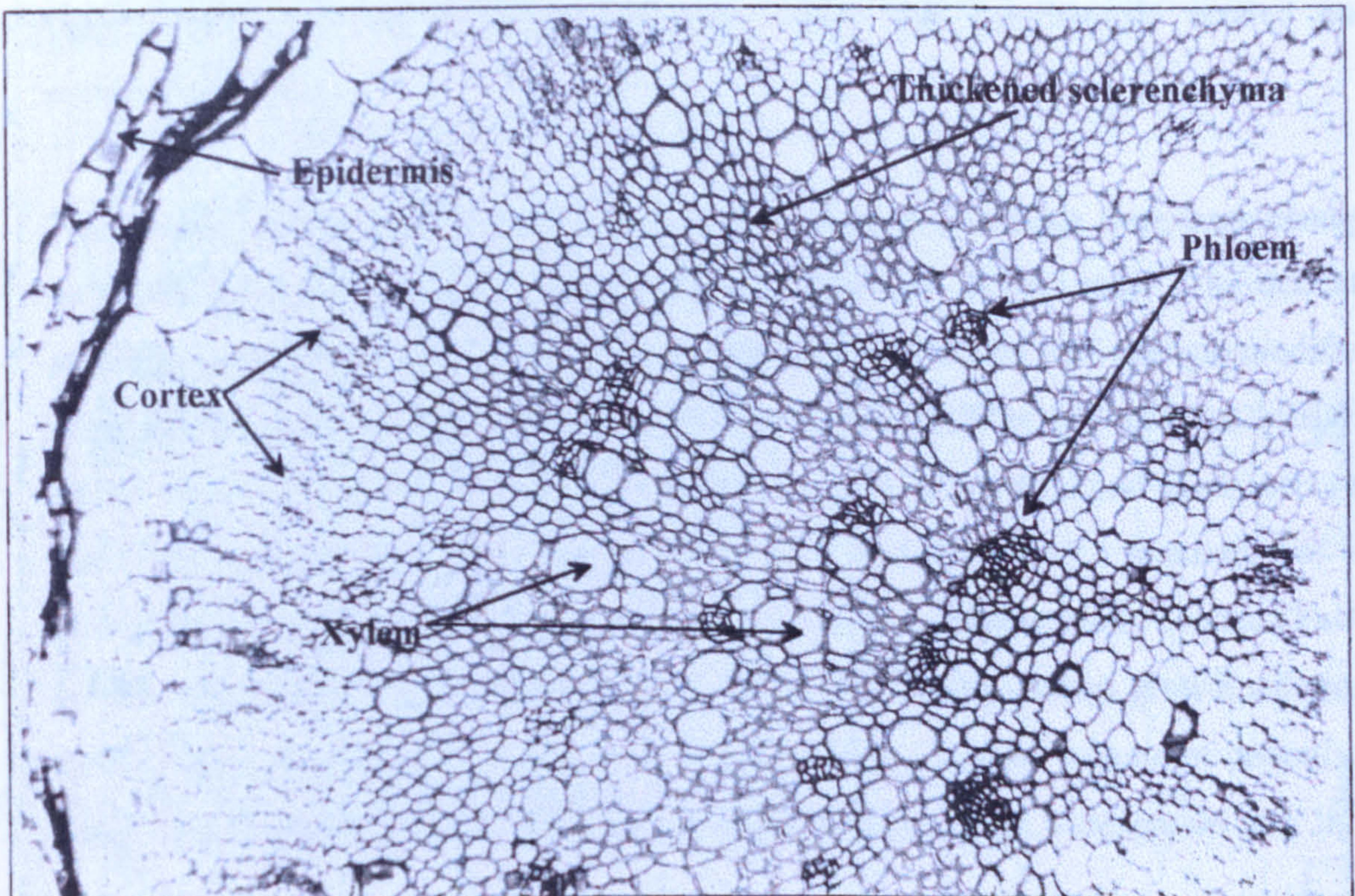
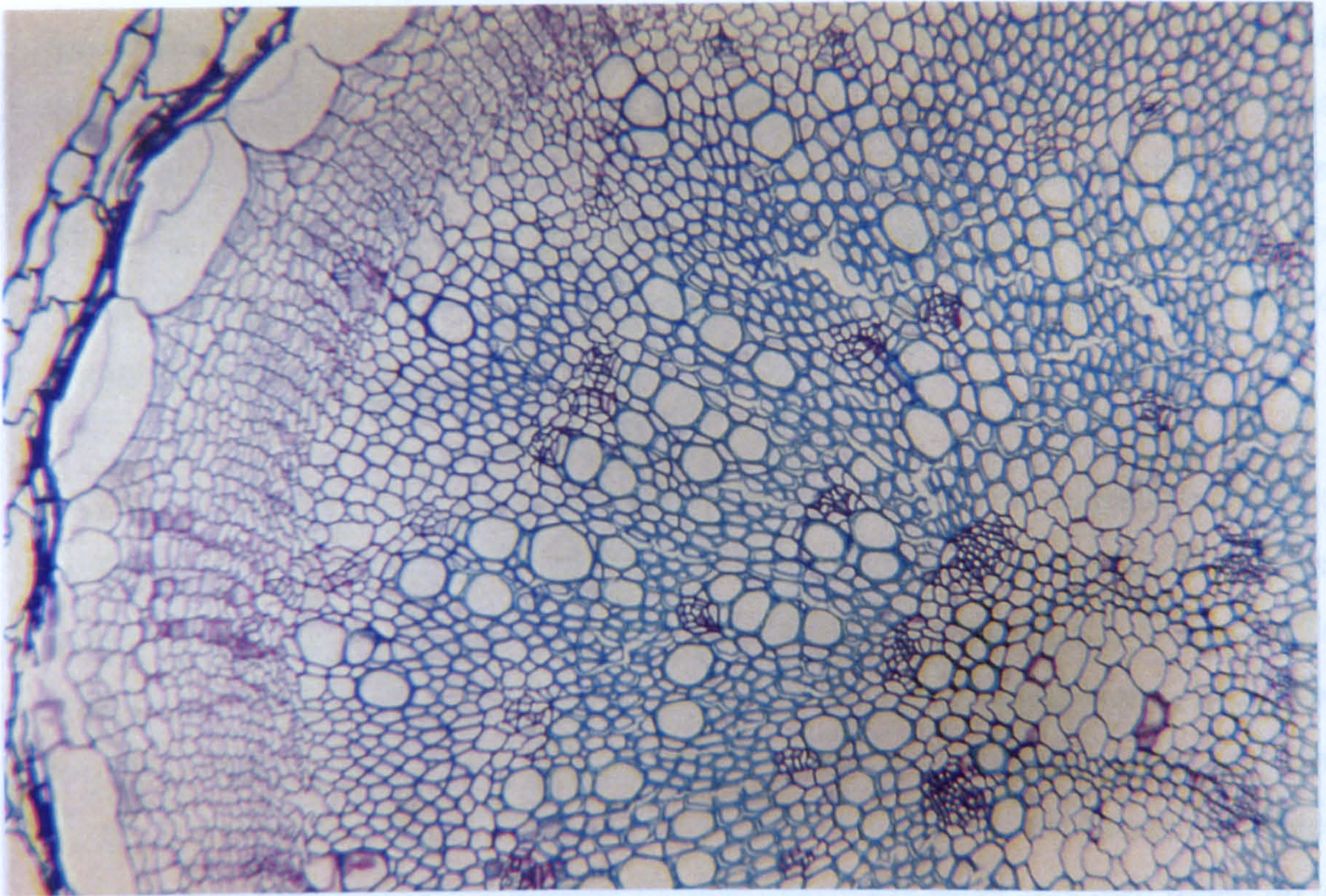


Photomicrograph 3.2, TS *Suaeda maritima* root ( x 400)





Photomicrograph 3.3, TS *Suaeda maritima* stem ( x 100)





## 3.2, Method

### 3.2.1, Germination and growth conditions

*Suaeda maritima* seeds were collected in mid October from a site on the Isle of Anglesey, grid reference SH 478650 (see also **Figure 3.2** and **Plate 3.1**). The seeds were spread out evenly on blue tissue paper and allowed to dry thoroughly at room temperature for four weeks. Following the drying procedure the seeds required a six week vernalisation period at 5 °C before germination. Any seeds not in use were stored in sealed plastic containers at 5 °C.

Prior to germination seeds were washed in de-ionised water in order to remove any mud or debris. It was unnecessary to remove the fruit coat, although many seeds had lost their coats naturally during the drying process, revealing the shiny black seed testa. To initiate germination the seeds were aerated in de-ionised water over night. The following day, using a spatula, the washed seeds were evenly spread in a thin line, two thirds of the way up a strip of blue tissue paper, which had been folded into three longitudinally and soaked in de-ionised water. The tissue paper was then rolled up to form a cylinder and placed in a 500 ml glass beaker containing a small volume (approximately 50 ml) of de-ionised water which was continuously aerated and replaced each day.

The first signs of germination were observed after 7 days. Seedlings were large enough to handle after 14 days and transferred to hydroponics at this stage. The delicate seedlings were transferred to 3 litre plastic containers containing half-strength modified Long Ashton growth solution (Hewitt, 1966) with either 0 mM or 200 mM NaCl (BDH) added. The seedlings were threaded through holes in a perspex lid and gently secured into place using custom made sponge plugs. Each container held a maximum of 16 plants. The growth medium was replaced every third day and adequately aerated (**Table 3.1** lists the components which make up a full-strength Long Ashton growth solution; the half-strength medium is simply prepared by adding an equal volume of de-ionised water to a volume of the full-strength solution). The seedlings were grown at a light



intensity of  $800 \mu\text{mol m}^{-2} \text{s}^{-1}$ , under a 16 hr/8 hr light/dark regime. Temperature was maintained at  $22 \text{ }^{\circ}\text{C}$  at a relative humidity of between 55 % and 60 %.

**Table 3.1, Composition of full-strength Long Ashton growth solution**

Macronutrient	Concentration (mM)
$\text{K}^+$	4
$\text{Ca}^{2+}$	4
$\text{Mg}^{2+}$	1.5
$\text{HPO}_4^{2-}$	1.3
$\text{SO}_4^{2-}$	1.5
$\text{NO}_3^-$	12

Micronutrient	Concentration (mM)
Si	0.05
$\text{Fe}^{2+}$	0.1
$\text{Mn}^{2+}$	0.01
$\text{Cu}^{2+}$	0.001
$\text{Zn}^{2+}$	0.001
$\text{Na}^+$	1.3
$\text{BO}_3^-$	$5 \times 10^{-5}$
$\text{MoO}_4^{2-}$	$4 \times 10^{-4}$

The growth medium was prepared using the following AnalaR grade salts supplied by BDH: potassium nitrate, calcium nitrate, sodium dihydrogenorthophosphate, magnesium sulphate, EDTA (Fe-Na salt), manganese sulphate, copper sulphate, zinc sulphate, boric acid and sodium molybdate.



### 3.2.2, Tissue preparation and section cutting for light microscopy

The tissue preparation and section cutting procedure used was modified from a protocol published by Feder and O'Brien in 1968. The plant material to be sectioned was fixed in 3 % glutaraldehyde (BDH) in 0.1 M phosphate buffer (BDH) in a vacuum oven at room temperature for 24 hours. The tissue was then dehydrated in a series of ethanol solutions (from 25 % to 100 % ethanol); the percentage ethanol was increased by 25 % each day. Once the dehydration procedure had been completed the plant tissue was placed in chloroform (Sigma Chemicals) for 30 minutes before being returned to 100 % ethanol.

To provide a support for the plant material during the section cutting procedure the tissue was embedded in polymerised Technovit 7100 resin (TAAB). To ensure effective infiltration of embedding medium throughout the tissue, the plant material was rotated over night in a 50/50 solution of 100 % ethanol and embedding resin. The tissue was then transferred to pure resin and left on the rotator for up to 5 days. The plant tissue was then carefully positioned in plastic moulds (TAAB) and covered in embedding resin which had been activated with a hardening agent to facilitate polymerisation and setting. The polymerisation process was complete within 3 hours. The resin blocks could then be shaped and fitted to the glass microtome ready for sectioning.

Sectioning was achieved using a glass knife microtome (Reichert-Jung, Germany). Placing a small amount of historesin glue (TAAB) on the upper edge of the resin block allowed a continuous ribbon of resin, 4  $\mu\text{m}$  thick, to be cut by the microtome. The resin ribbons were immediately placed in a water bath and gently scooped onto a glass microscope slide. Once the slides were dry the sections were stained using Toluidine Blue (BDH) until the desired level of staining was achieved (60 seconds is usually adequate). The slides were then washed with de-ionised water to remove the excess stain, and dried. The sections were permanently mounted on the slide using a mounting medium and a cover slip.



### 3.2.3, Turgor pressure and single cell sampling and analysis

For leaf analysis, plants were selected 14 days after transfer to hydroponics (day 14), placed into individual 10 ml pots containing a small sample of the appropriate hydroponic medium, and fixed to the adjustable microscope stage adjacent to the cell pressure probe and sampling arm. The cells targeted for pressure probe and single cell sampling and analysis work were epidermal cells on leaf pair 1 and 2. Securing the plants firmly prior to probing was a problem due to the cylindrical shape and delicate nature of the leaves. This problem was overcome by threading a double length of cotton through a glass pipette to form a loop at the tip. The pipette was then fixed to the microscope stage enabling the cotton loop to be placed over a selected leaf. The loop could then be gently pulled tight and kept taut using a small weight on the free end of the cotton thread. The loop method secured a section of leaf (approximately 2 - 3 mm either side of the loop) firmly enough to pressure probe and sample successfully. The apparatus set up is illustrated in Figure 3.3. Measurements were made on 5 plants per treatment (approximately 3 hours into the photoperiod), and a minimum of three cells were targeted on each leaf.

The majority of the experiments were carried out on transpiring plants. However, measurements under non-transpiring conditions were achieved by coating the leaves with a thin layer of petroleum jelly, using a fine paint brush. This procedure was assumed to completely inhibit transpiration by blocking the stomatal pores. After coating the leaves the plants were returned to the growth facility for 30 minutes before any measurements were taken.

For root analysis, plants were selected at day 21. *Suaeda maritima* has a very fine root system which is too fragile to probe and sample successfully at day 14. However, by day 21 the root system is sufficiently robust to withstand the pressure probing and sampling procedure. Each plant was carefully removed from its hydroponic container, and the root system rinsed in fresh hydroponic solution for 5 minutes. A 3 cm length of root, measured from the tip towards the shoot, was secured to the base of a shallow perspex sample holder. The secured length of root was not detached from the rest of the root or shoot at any time. Once in position the entire root was covered in 10 - 15 ml of fresh



hydroponic solution. The shoot was simply allowed to rest against the side of the sample holder. The target cells were outer cortex cells situated approximately 1 cm from the root tip. Due to their small volume it was necessary to combine up to 5 individual cell samples in order to obtain an adequate volume of cell sap for analysis. Turgor pressure root analysis required 5 plants per treatment; at least 3 root cortex cells were targeted per plant. Sap samples were obtained from 15 plants per treatment.

### **3.2.4, Xylem pressure**

Xylem pressure measurements using the xylem pressure probe ( $P_{\text{xylem}}$ ) were made in the stem at day 14 and day 21. Plants were placed in a 300 ml sample holder (containing the appropriate growth medium), which was clamped firmly to a retort stand and positioned at the desired level for probing. The stem was secured to an adjustable clamp arm with cotton thread. All measurements were made three hours into the photoperiod. Data was presented in relation to atmospheric pressure rather than in absolute terms.

### **3.2.5, Step-up/step-down protocol**

Plants subjected to a “Step-up” or “Step-down” treatment experienced an up or down osmotic shock of about 1 MPa respectively. Osmotic shock was achieved simply by swapping the hydroponic media. Plants grown initially in the 0 mM NaCl medium were given a 1 MPa step-up by being transferred to the 200 mM NaCl medium. Conversely, plants grown in the 200 mM NaCl medium were given a 1 MPa step-down by being transferred to the 0 mM NaCl hydroponic medium. Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $P_{\text{cell}}$ ) measurements were made in the leaves and root at the times indicated. Single cell samples for EDX analysis were taken prior to the step-up/step-down treatment and 24 hours after the treatment.

A step-up/step-down treatment during a xylem pressure probe experiment was a little more involved. A 1 MPa step-up/step-down was applied to the root system while the tip of the glass microcapillary was inside a xylem vessel in the stem. This was achieved using a modified 300 ml sample holder connected to a three way tap system and a funnel reservoir. This specialised apparatus allowed the original hydroponic medium to



be drained away and replaced by the step-up/step-down medium stored in the funnel reservoir. It was essential that the hydroponic medium was changed quickly and smoothly with minimal disturbance to the plant (any vibration could potentially dislodge the glass microcapillary and bring the experiment to an abrupt end). The whole procedure took no longer than 30 seconds.

### **3.2.6, Statistical analysis**

The statistical analysis tool used was a paired (matched) t-Test. Microsoft Excel Version 7.0 was used to generate exact p values which are reported as is in the results section which follows (see Section 3.3). If the p value generated is equal to or less than a predetermined alpha value (which in the literature, is often 0.05 or 0.01) the Null Hypothesis put forward can be rejected. In the following experiments the Null Hypothesis to be tested states that the population mean in treatment one and treatment two are equal.



Figure 3.2, Seed collection site on the Isle of Angelsey

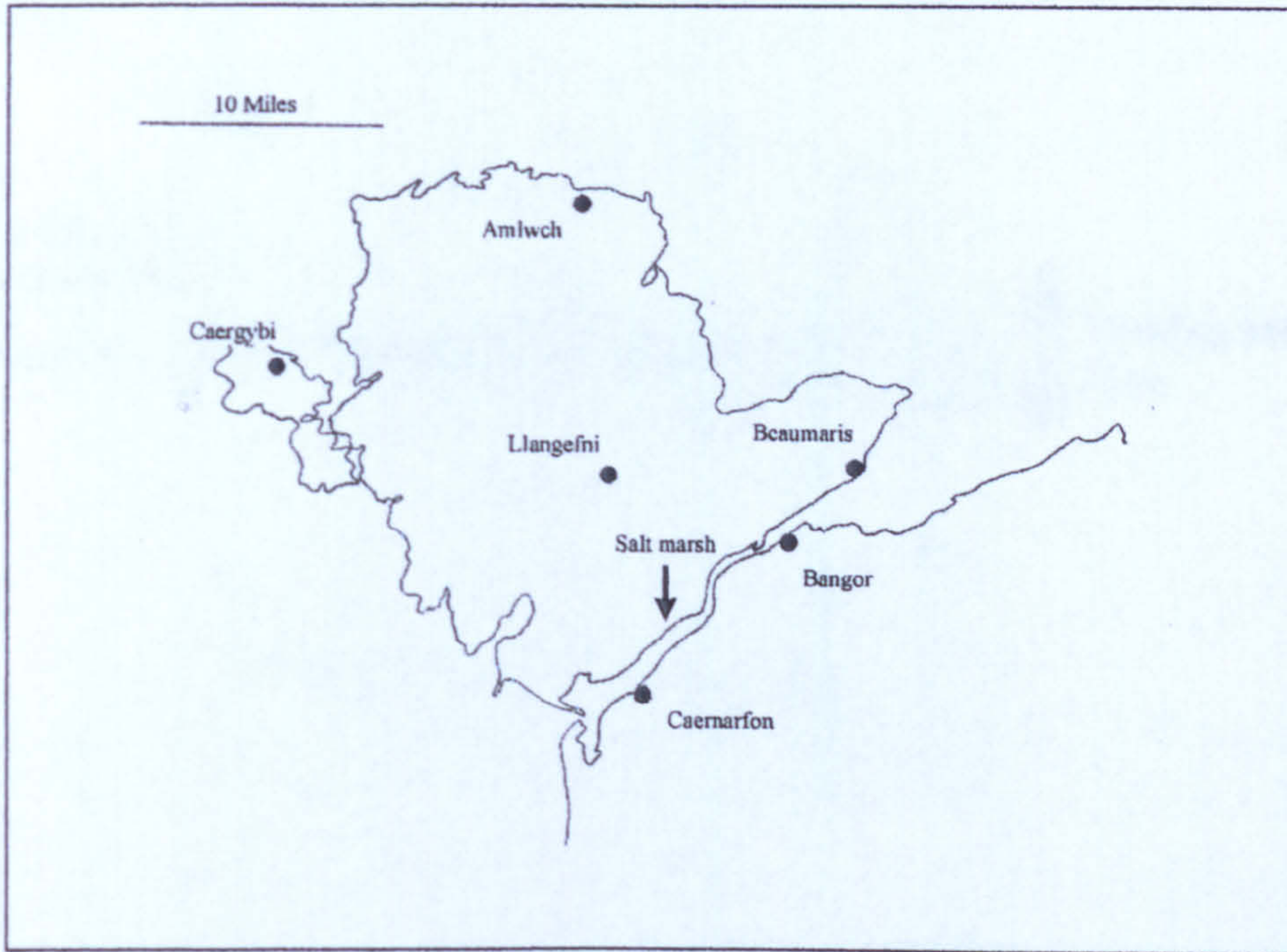


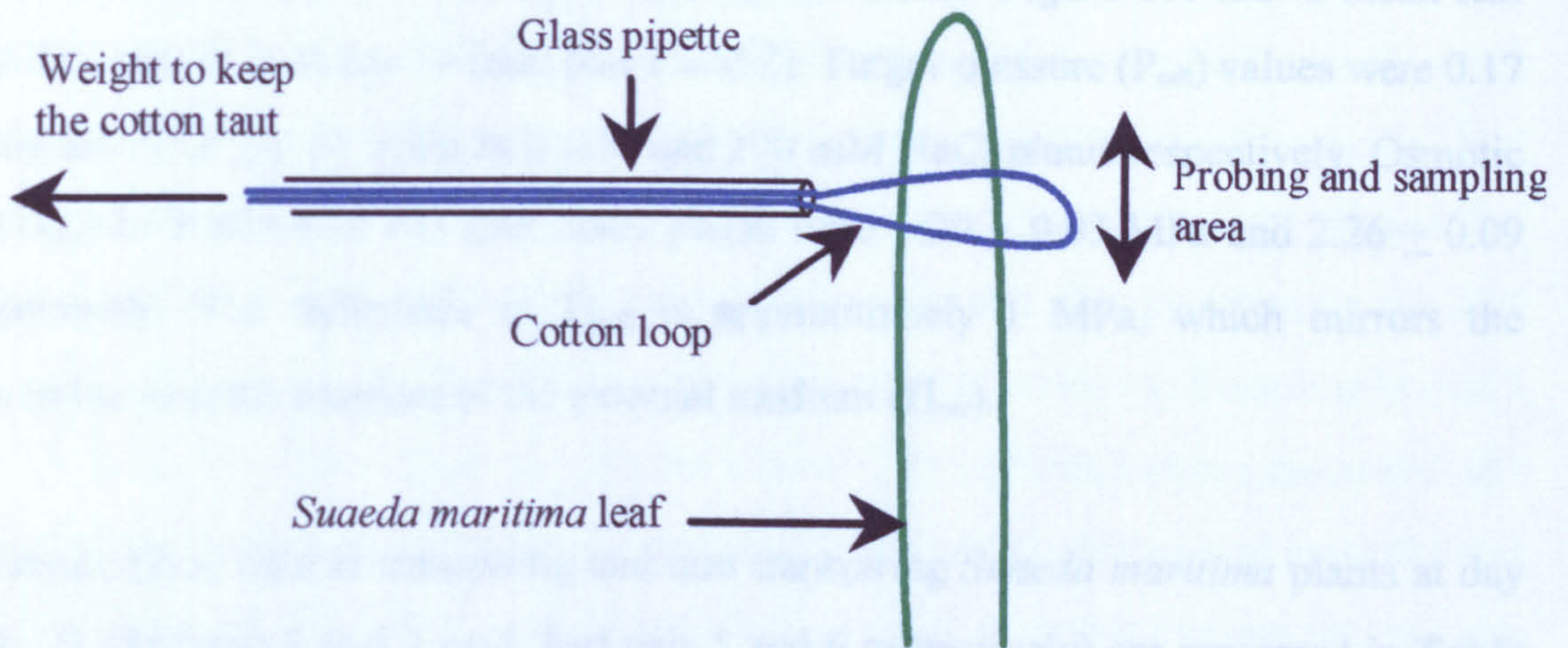
Plate 3.1, *Suaeda maritima* in its natural environment





**Figure 3.3, *Suaeda maritima* leaf securing system**

The glass pipette and cotton loop system used to secure a *Suaeda maritima* leaf (which is still attached to the plant) prior to turgor pressure measurements and single cell sampling.



Leaf turgor pressure (P<sub>td</sub>) and osmotic pressure (Π<sub>td</sub>) data in plants exposed to 0, 50, and 100 mM NaCl are presented in Table 3.4. Figure 3.4 shows mean leaf turgor pressure (P<sub>td</sub>) values were 0.17 MPa in the control, 0.20 MPa in the 50 mM NaCl treatment, and 0.23 MPa in the 100 mM NaCl treatment. Turgor pressure (P<sub>td</sub>) measurements after leaf was cut by the glass pipette from the clearest central vessels (approximately 0.2 MPa) (Fig. 3.3) were included in the figure legend.

Plants were subjected to a step-up and step-down in osmotic pressure (Π<sub>td</sub>) 24 hours after the initial step-up/step-down treatment. Large changes in P<sub>td</sub> were observed in the step-up and step-down treated plants were 0.18 ± 0.02 MPa and 0.20 ± 0.02 MPa respectively, which are comparable to P<sub>td</sub> in the 0 mM and 50 mM NaCl treatments (0.17 ± 0.01 MPa and 0.20 ± 0.01 MPa respectively). Osmotic pressure (Π<sub>td</sub>) in the step-up treated plants increased from 1.43 ± 0.06 MPa to 2.45 ± 0.07 MPa, an increase of 1.02 MPa, corresponding to the step-up in osmotic pressure applied to the root.



### 3.3, Results

The cell pressure probe and single cell sampling and analysis techniques were used to obtain *Suaeda maritima* leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) data in plants grown in 0 mM and 200 mM NaCl hydroponic media. Figure 3.4 shows mean leaf epidermal  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  at day 14 (leaf pair 1 and 2). Turgor pressure ( $P_{\text{cell}}$ ) values were  $0.17 \pm 0.03$  MPa and  $0.18 \pm 0.03$  MPa in 0 mM and 200 mM NaCl plants respectively. Osmotic pressure ( $\Pi_{\text{cell}}$ ) in 0 mM and 200 mM NaCl plants were  $1.20 \pm 0.03$  MPa and  $2.26 \pm 0.09$  MPa respectively. The difference in  $\Pi_{\text{cell}}$  is approximately 1 MPa, which mirrors the difference in the osmotic pressure of the external medium ( $\Pi_{\text{ext}}$ ).

Turgor pressure ( $P_{\text{cell}}$ ) data in transpiring and non transpiring *Suaeda maritima* plants at day 14 and day 21 (leaf pair 1 and 2, and leaf pair 5 and 6 respectively) are presented in Table 3.2. At day 14 there was no statistical difference between  $P_{\text{cell}}$  in transpiring and non-transpiring plants. By day 21, however,  $P_{\text{cell}}$  in non-transpiring plants was greater than  $P_{\text{cell}}$  in transpiring plants by approximately 0.1 MPa.

Leaf epidermal (day 14, leaf pair 1 and 2) turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) measurements were taken in plants subjected to a step-up or step-down of 1 MPa in the external medium. Turgor pressure ( $P_{\text{cell}}$ ) measurements were taken 10 minutes after applying the step-up/step-down treatment (given that the treatment was applied at time 0), and at 30 minute intervals thereafter for a maximum of 2 hours (Figure 3.5). Control measurements (prior to treatment) are indicated at time 0. Turgor pressure ( $P_{\text{cell}}$ ) measurements after treatment did not deviate statistically from the observed control values (approximately 0.2 MPa). The p values generated for each treatment are included in the figure legend.

Figure 3.6 illustrates leaf epidermal  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  24 hours after the initial step-up/step-down treatment. Turgor pressure ( $P_{\text{cell}}$ ) in the step-up and step-down treated plants were  $0.18 \pm 0.02$  MPa and  $0.19 \pm 0.02$  MPa respectively; values which are comparable to  $P_{\text{cell}}$  in the 0 mM and 200 mM NaCl control plants ( $0.17 \pm 0.03$  MPa and  $0.18 \pm 0.03$  MPa respectively). Osmotic pressure ( $\Pi_{\text{cell}}$ ) in step-up plants increased from  $1.42 \pm 0.06$  MPa to  $2.46 \pm 0.07$  MPa, an increase of 1 MPa, which is equivalent to the step-up in osmotic pressure applied to the root



system. However,  $\Pi_{\text{cell}}$  in step-down plants did not mirror the 1 MPa decrease in the external medium. The osmotic pressure ( $\Pi_{\text{cell}}$ ) in step-down plants was  $2.37 \pm 0.1$  MPa compared to  $2.58 \pm 0.03$  MPa in the 200 mM NaCl control plants (a maximum decrease in  $\Pi_{\text{cell}}$  of only 0.2 MPa).

X-ray microanalysis (EDX analysis) was used to determine the mean sodium, chloride, potassium and calcium content of sap samples taken from leaf epidermal cells (day 14, leaf pair 1 and 2) in control and step-up/step-down treated *Suaeda maritima* plants. Figure 3.7 illustrates the Na, Cl, K and Ca content of leaf epidermal vacuolar samples taken from 0 mM and 200 mM NaCl plants. The Na and Cl content in vacuolar samples from 0 mM NaCl plants were negligible. Whereas samples taken from the 200 mM NaCl plants contained  $563 \pm 171$  mM sodium and  $313 \pm 91$  mM chloride. The potassium concentrations in 0 mM and 200 mM NaCl plants were  $152 \pm 59$  mM and  $29 \pm 26$  mM respectively, and the calcium concentrations in 0 mM and 200 mM NaCl plants were  $13 \pm 23$  mM and  $-5 \pm 10$  mM respectively.

Changes in Na and Cl content after a 24 hour step-up/step-down treatment are illustrated in Figure 3.8 and Figure 3.9. Step-up plants accumulated  $397 \pm 104$  mM Na and  $362 \pm 77$  mM Cl during the 24 hour treatment period. From the step-down data it could be argued that plants subjected to a 1 MPa step-down mobilised Na out of the vacuole during the 24 hour treatment. However, the decrease from  $563 \pm 171$  mM in control plants (200 mM NaCl) to  $424 \pm 136$  mM (step-down plants) is not statistically different at the 0.01 alpha level and is likely to be due to natural plant variation and/or sampling error. There was no evidence to suggest that chloride was mobilised out of the vacuole, chloride concentrations in step-down treated plants ( $286 \pm 98$  mM) remained comparable to the control ( $362 \pm 77$  mM). The mean and standard deviation for each element analysed in control and treated plants are presented in Table 3.3, along with the p values generated from the paired t-Test.

In Table 3.4 the EDX data are presented alongside corresponding osmotic pressure ( $\Pi_{\text{cell}}$ ) data. This allows a comparison of the  $\Pi_{\text{cell}}$  data with the sum of the solutes measured by X-ray microanalysis. Before a direct comparison can be made, however, the sum solute values must be multiplied by the appropriate osmotic coefficient ( $\phi$ ). The osmotic coefficient



takes into account the deviation of a solution away from ideality (see Wyn Jones and Gorham, 1983). An osmotic coefficient of 0.82 was used in this study - after Fricke *et al.*, 1994 (see also Malone *et al.*, 1991). Any discrepancy between the measured  $\Pi_{\text{cell}}$  and calculated  $\Pi_{\text{cell}}$  (calculated from the sum of solutes multiplied by the osmotic coefficient) may highlight the presence of additional, unmeasured solutes in the analysed sap samples. The largest discrepancy between measured  $\Pi_{\text{cell}}$  and calculated  $\Pi_{\text{cell}}$  values was observed in the leaf epidermal cells of 0 mM NaCl treated *Suaeda maritima* plants (see Table 3.4). Subtracting the calculated  $\Pi_{\text{cell}}$  from the measured  $\Pi_{\text{cell}}$  revealed that 429.3 mOsmol kg<sup>-1</sup> (approximately 1.07 MPa) is unaccounted for in 0 mM NaCl plants, 309.15 mOsmol kg<sup>-1</sup> (0.77 MPa) and 254.14 mOsmol kg<sup>-1</sup> (0.6 MPa) is unaccounted for in step-down and step-up plants respectively and 185.76 mOsmol kg<sup>-1</sup> (about 0.46 MPa) is unaccounted for in 200 mM NaCl treated plants. These data strongly suggest that other osmotically active solutes are present in the sap samples taken from *Suaeda maritima* leaf epidermal cells. Possible candidates include P<sub>i</sub>, NO<sub>3</sub><sup>-</sup> and organic solutes such as malate (Fricke *et al.*, 1994; Bates, 1998).

Corresponding turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) data were obtained from root cortex cells situated 1 cm from the root tip at day 21. Measurements were made in control and step-up/step-down treated plants. Figure 3.10 illustrates root cortex turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in *Suaeda maritima* plants grown in 0 mM and 200 mM NaCl. Turgor pressure ( $P_{\text{cell}}$ ) was comparable in both 0 mM and 200 mM NaCl plants at  $0.39 \pm 0.03$  MPa and  $0.38 \pm 0.02$  MPa respectively. Root cortex osmotic pressure ( $\Pi_{\text{cell}}$ ) was  $0.43 \pm 0.12$  MPa and  $1.38 \pm 0.11$  MPa in 0 mM and 200 mM NaCl plants respectively. The difference in root cortex  $\Pi_{\text{cell}}$  is approximately 1 MPa, which corresponds with the difference in  $\Pi_{\text{cell}}$  observed in the leaf epidermal cells (see Figure 3.4), and once again mirrors the difference in the osmotic pressure of the external medium ( $\Pi_{\text{ext}}$ ).

A 1 MPa step-up/step-down treatment dramatically influenced the turgor pressure ( $P_{\text{cell}}$ ) of the root cortex cells. Figure 3.11 illustrates root cortex  $P_{\text{cell}}$  in control plants prior to treatment (time 0) and root cortex  $P_{\text{cell}}$  in treated plants at the times indicated in the figure legend. Root cortex  $P_{\text{cell}}$  in step-up plants fell rapidly within 10 minutes of applying the treatment. Attempts to measure  $P_{\text{cell}}$  were unsuccessful indicating that  $P_{\text{cell}}$  was either extremely low or



that the cells had undergone plasmolysis. No  $P_{\text{cell}}$  recovery was observed during the experiment. In contrast, the root cortex cells in step-down treated plants experienced a huge increase in  $P_{\text{cell}}$  within the same time period;  $P_{\text{cell}}$  increased from  $0.38 \pm 0.02$  MPa to  $1.29 \pm 0.03$  MPa within 10 minutes. Subsequent measurements taken at 30 minute intervals indicated that  $P_{\text{cell}}$  was decreasing, suggesting that  $P_{\text{cell}}$  regulation was taking place. Seven hours (420 minutes) after applying the step-down treatment  $P_{\text{cell}}$  had reached  $0.72 \pm 0.03$  MPa, which is a decrease of 0.6 MPa. The observed root cortex  $P_{\text{cell}}$  decrease in step-down plants was accompanied by an equivalent decrease in  $\Pi_{\text{cell}}$ . **Table 3.4** presents root cortex  $\Pi_{\text{cell}}$  data taken in control (0 mM and 200 mM) and treated (step-up/step-down) plants at the times indicated. Seven hours (420 minutes) after applying the step-down treatment  $\Pi_{\text{cell}}$  had decreased from  $1.38 \pm 0.11$  MPa to  $0.81 \pm 0.02$  MPa, a decrease of 0.6 MPa. Osmotic pressure ( $\Pi_{\text{cell}}$ ) in step-up plants after 7 hours could not be determined due to difficulty in obtaining a sample.

Root cortex turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) data taken 24 hours after a step-up/step-down treatments are illustrated in **Figure 3.12**. Step-up and step-down treated plants regulated  $P_{\text{cell}}$  upwards and downwards respectively to a level comparable to  $P_{\text{cell}}$  in control plants (approximately 0.4 MPa), within 24 hours. Osmotic pressure ( $\Pi_{\text{cell}}$ ) increased by 1 MPa (from  $0.43 \pm 0.12$  MPa to  $1.32 \pm 0.07$  MPa) in step-up plants and decreased by 1 MPa (from  $1.38 \pm 0.11$  MPa to  $0.40 \pm 0.05$  MPa) in step-down plants over the 24 hour period. These changes in  $\Pi_{\text{cell}}$  exactly mirror the changes in the external medium ( $\Pi_{\text{ext}}$ ). These data are also presented in **Table 3.5**.

Xylem pressure probe measurements were made in the stem of control and step-up/step-down treated *Suaeda maritima* plants, at day 14 and day 21. The aim was to ascertain whether applying an osmotic shock treatment to the root system would lead to the propagation of a hydrostatic signal to the shoot, via the xylem. **Figure 3.13** and **Figure 3.14** show the distribution of xylem pressure measured in *Suaeda maritima* stems at day 14 and day 21. Measurements were made in both 0 mM and 200 mM NaCl plants. The xylem pressure measurements obtained ranged from -0.005 MPa to -0.055 MPa. The level of xylem pressure most commonly observed was around -0.005 MPa in each case, although the older, larger plants (day 21) showed an increased number of greater (more negative)  $P_{\text{xylem}}$  values.

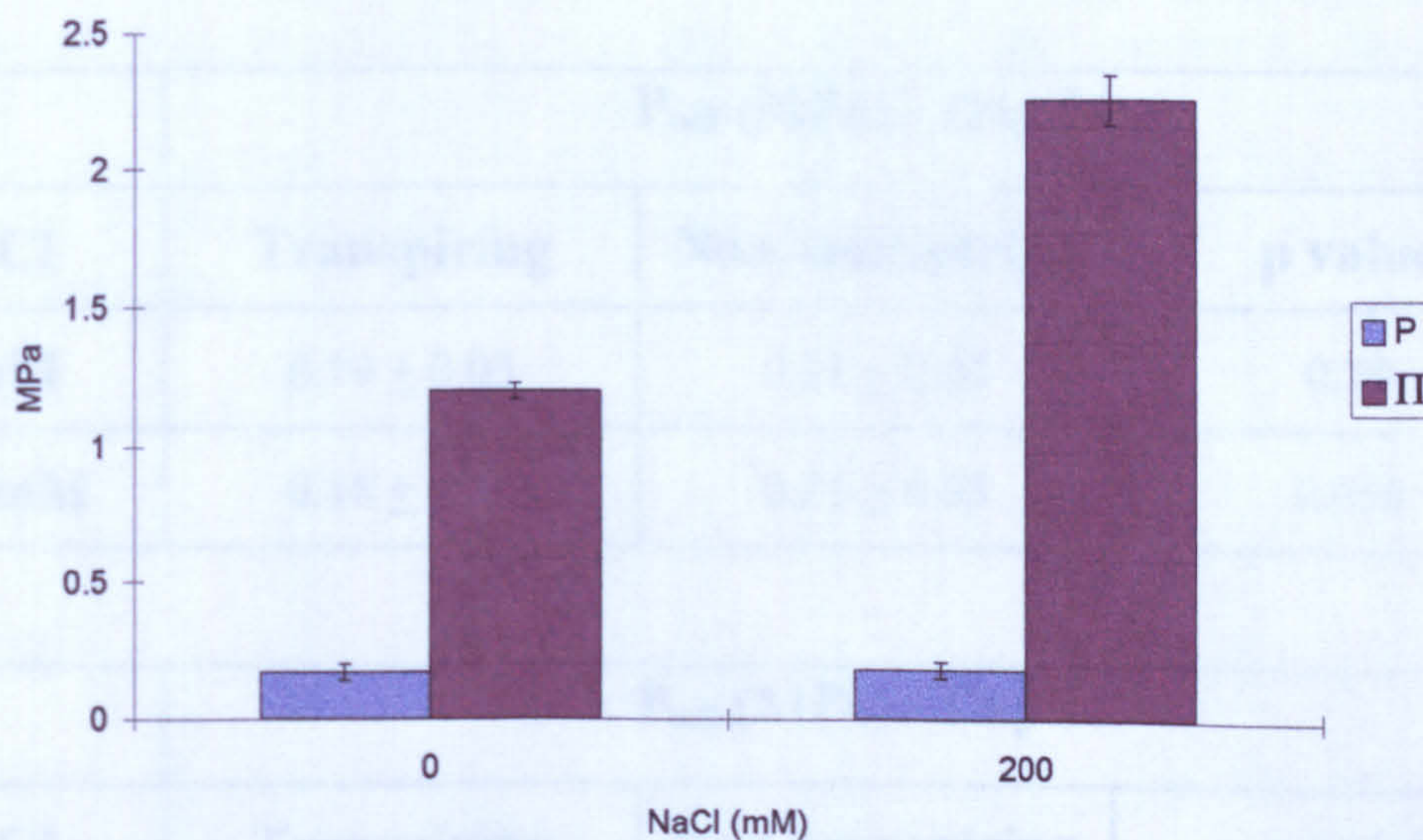


**Figure 3.15** and **Figure 3.16** show typical xylem probe traces obtained from 0 mM and 200 mM NaCl plants respectively, at day 21. These images have been scanned into the text from the original chart recorder print outs. The small peaks running along the traces are pressure pulses applied manually to the system. A step-up/step-down treatment was applied to the root system approximately 5 minutes into a xylem pressure ( $P_{\text{xylem}}$ ) measurement. The point at which the root medium was changed is highlighted by an arrow on each figure. No change in xylem pressure was observed after a step-up or step-down treatment. This indicates that there is either no hydrostatic signal generated or that the signal is undetectable. The xylem probe traces illustrated are representative examples of experiments carried out on at least 15 plants per treatment.



**Figure 3.4,  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  in *Suaeda maritima* leaf epidermal cells at day 14**

Mean turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in leaf epidermal cells (leaf pair 1 and 2) at day 14. The error bars indicate standard deviation, n is 15 leaf epidermal cells (5 plants, 3 cells per plant). The statistical analysis tool used was a paired t-Test. The  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  p values generated were 0.86 and  $4.48 \times 10^{-9}$  respectively.





**Table 3.2, Leaf epidermal  $P_{cell}$  in transpiring and non-transpiring *Suaeda maritima* plants**

Mean turgor pressure ( $P_{cell}$ ) in leaf epidermal cells in transpiring and non-transpiring *Suaeda maritima* plants, at day 14 (leaf pair 1 and 2) and day 21 (leaf pair 5 and 6). The  $\pm$  values indicate standard deviation, n is 15 leaf epidermal cells (5 plants, 3 cells per plant). The statistical analysis tool used was a paired t-Test. The p values generated are as indicated in the table.

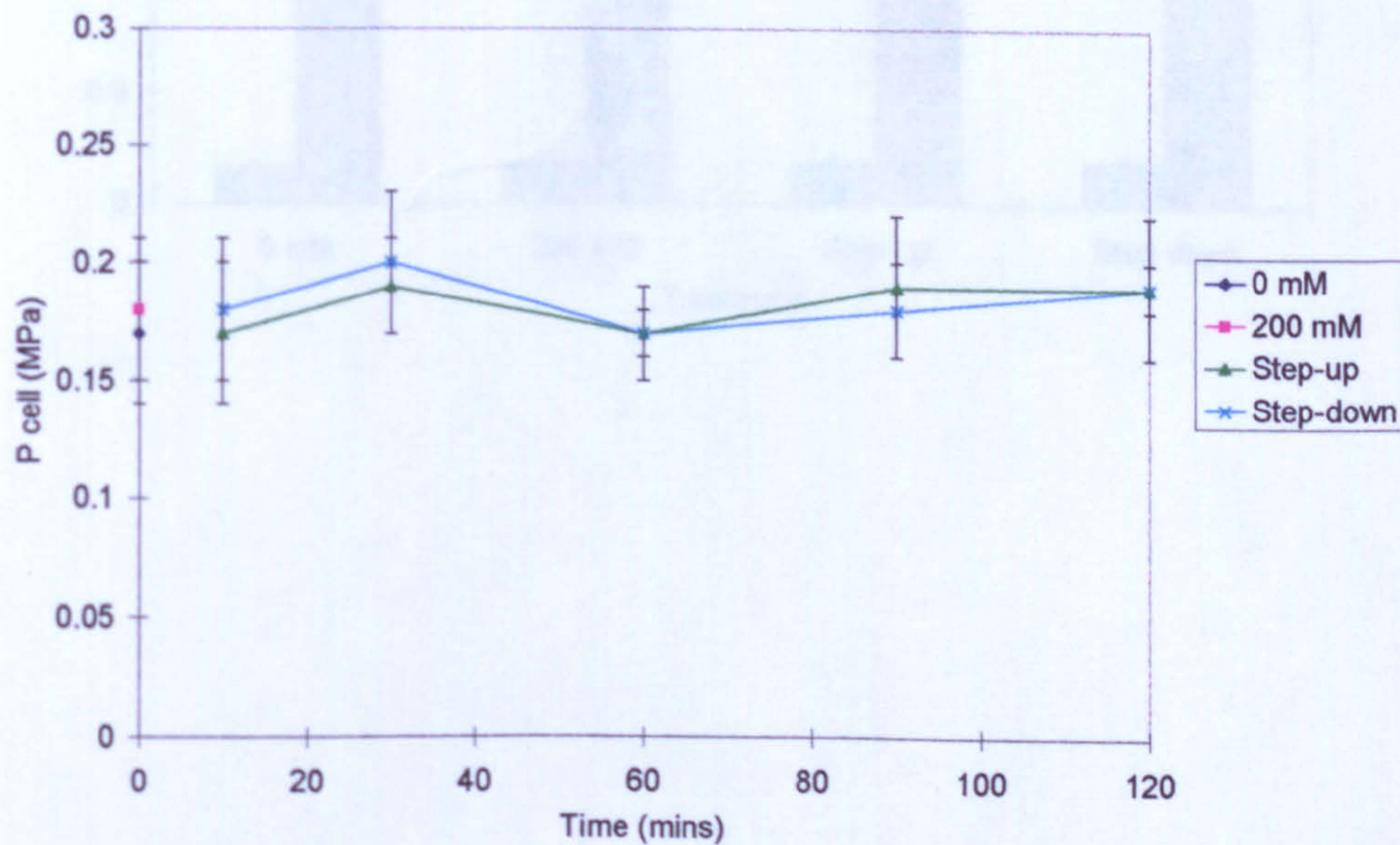
	$P_{cell}$ (MPa) - Day 14		
NaCl	Transpiring	Non-transpiring	p value
0 mM	0.19 $\pm$ 0.03	0.21 $\pm$ 0.03	0.19
200 mM	0.18 $\pm$ 0.02	0.21 $\pm$ 0.03	0.056

	$P_{cell}$ (MPa) - Day 21		
NaCl	Transpiring	Non-transpiring	p value
0 mM	0.18 $\pm$ 0.02	0.32 $\pm$ 0.02	0.0005
200 mM	0.19 $\pm$ 0.02	0.30 $\pm$ 0.02	7.34 x 10 <sup>-5</sup>



**Figure 3.5, Leaf epidermal  $P_{cell}$  in *Suaeda maritima* plants subjected to a step-up/step-down treatment**

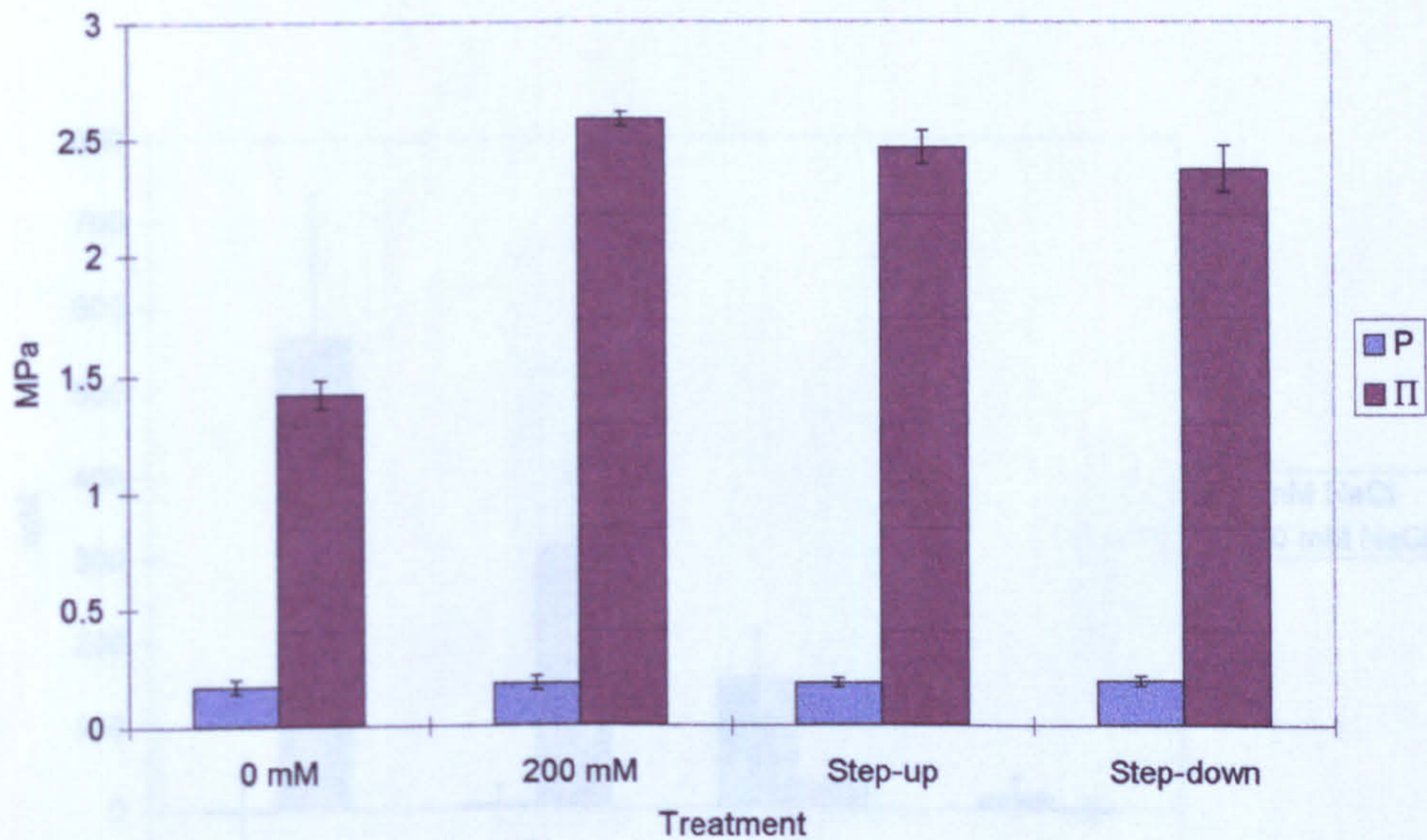
Mean leaf epidermal turgor pressure ( $P_{cell}$ ) in *Suaeda maritima* plants subjected to a step-up or step-down of 1 MPa in the external (hydroponic) medium at day 14 (leaf pair 1 and 2). Step-up plants were given a 1 MPa up shock from 0 mM to 200 mM NaCl, whereas step-down plants were given a 1 MPa down shock from 200 mM to 0 mM NaCl.  $P_{cell}$  measurements were taken prior to treatment (Time 0) and at the times indicated after treatment. The error bars indicate standard deviation, n is 15 cells (5 plants, 3 cells per plant). A paired t-Test was used to compare mean  $P_{cell}$  in control plants (at time 0) with mean  $P_{cell}$  at each time interval after treatment. The p values generated are as follows: Step-up plants at 10, 30, 60, 90 and 120 minutes after treatment had p values of 1.0, 0.49, 0.91, 0.56, and 0.39 respectively. Step-down plants at 10, 30, 60, 90 and 120 minutes after treatment had p values of 0.87, 0.11, 0.43, 1.0, and 0.62 respectively.





**Figure 3.6,  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  in *Suaeda maritima* leaf epidermal cells 24 hours after a step-up/step-down treatment**

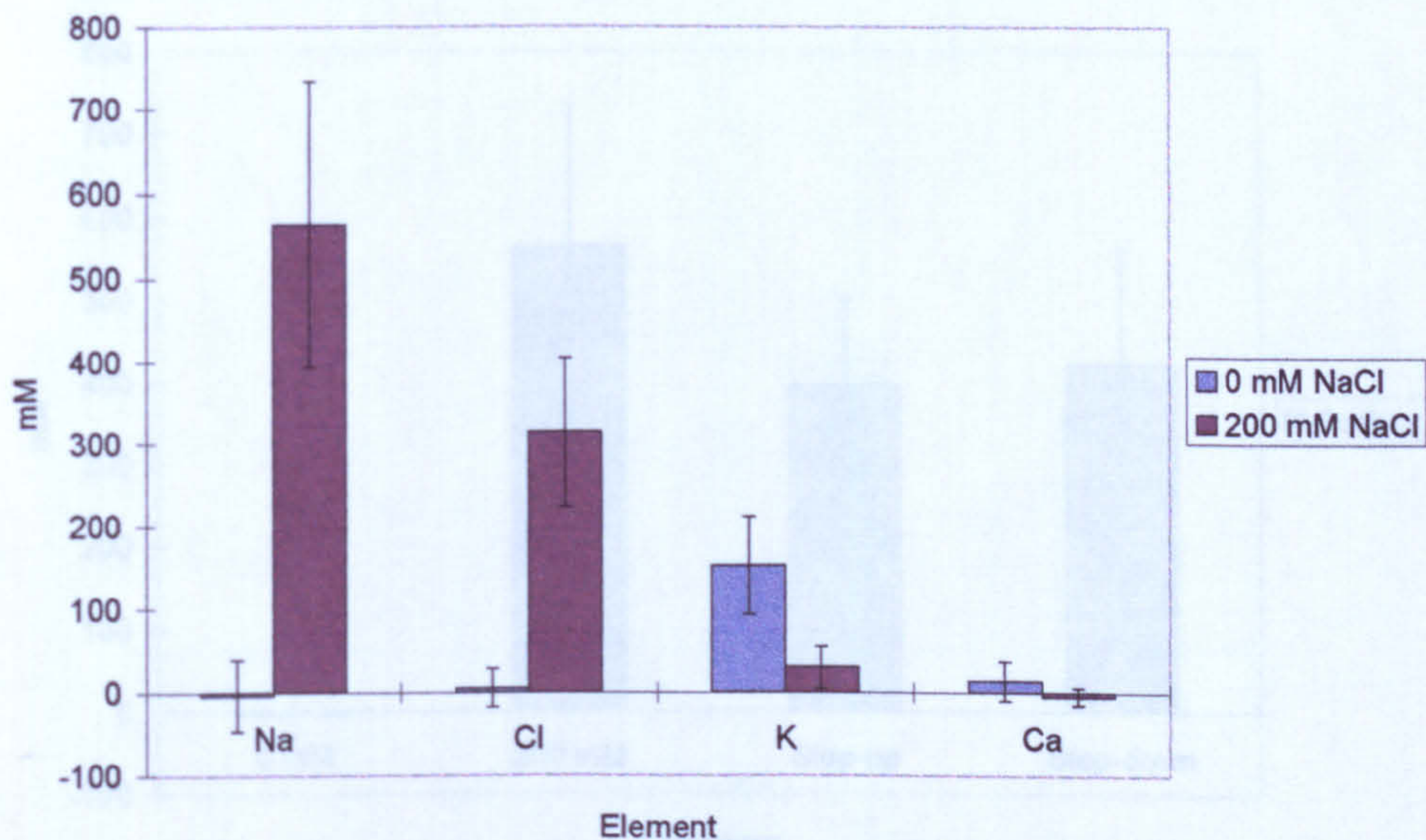
Mean turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in *Suaeda maritima* leaf epidermal cells 24 hours after a step-up/step-down treatment (day 15, leaf pair 1 and 2). Error bars indicate standard deviation, n is 15 cells (5 plants, 3 cells per plant).





**Figure 3.7, Sodium, chloride, potassium and calcium concentrations in sap samples taken from leaf epidermal cells in *Suaeda maritima* plants grown in 0 mM and 200 mM NaCl**

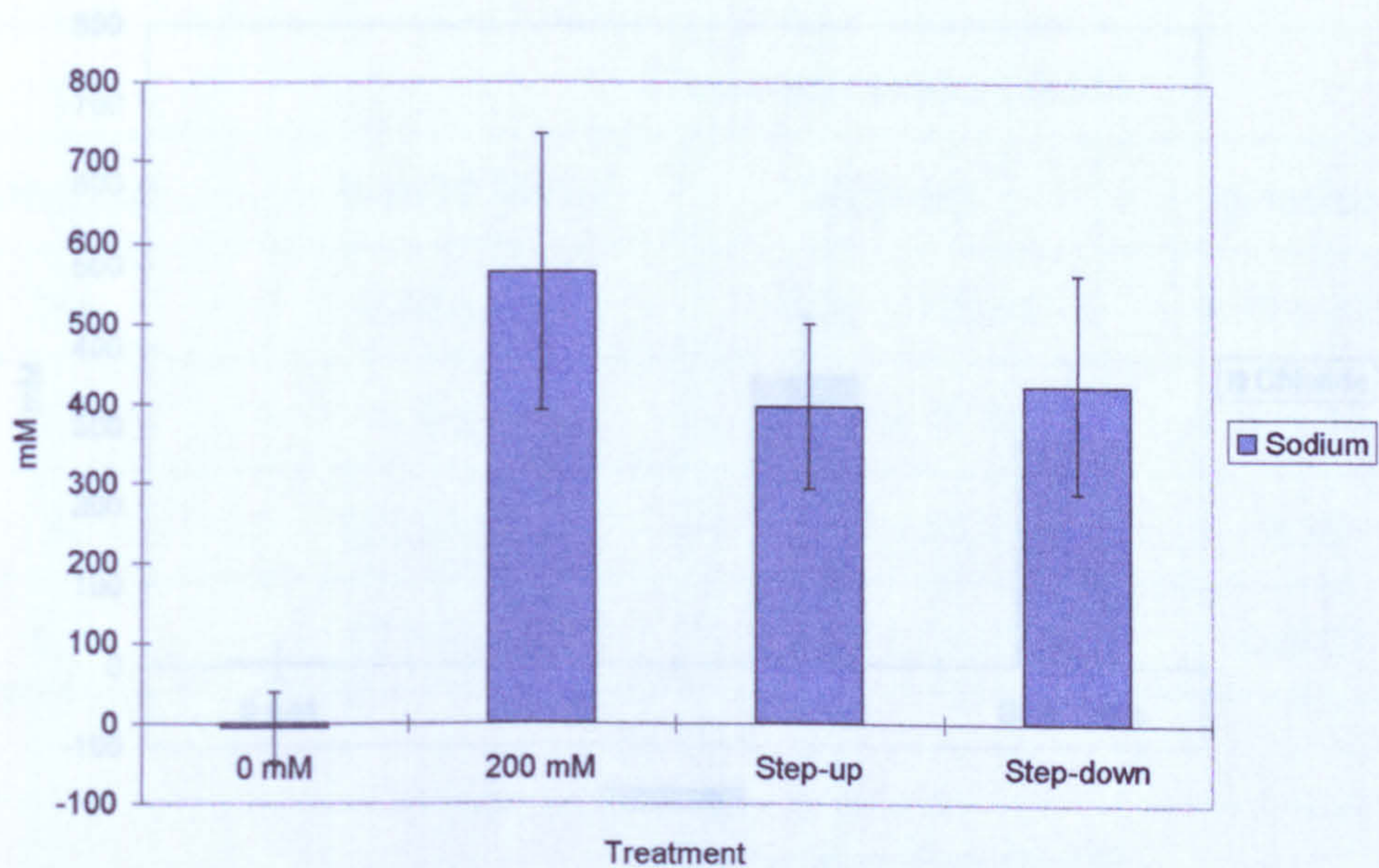
Mean sodium, chloride, potassium and calcium concentrations in sap samples taken from leaf epidermal cells in *Suaeda maritima* plants grown in 0 mM and 200 mM NaCl at day 14 (leaf pair 1 and 2). Error bars indicate standard deviation, n is 15 cells (5 plants, 3 cells per plant).





**Figure 3.8, Sodium concentration in leaf epidermal sap samples taken from *Suaeda maritima* plants 24 hours after a step-up/step-down treatment**

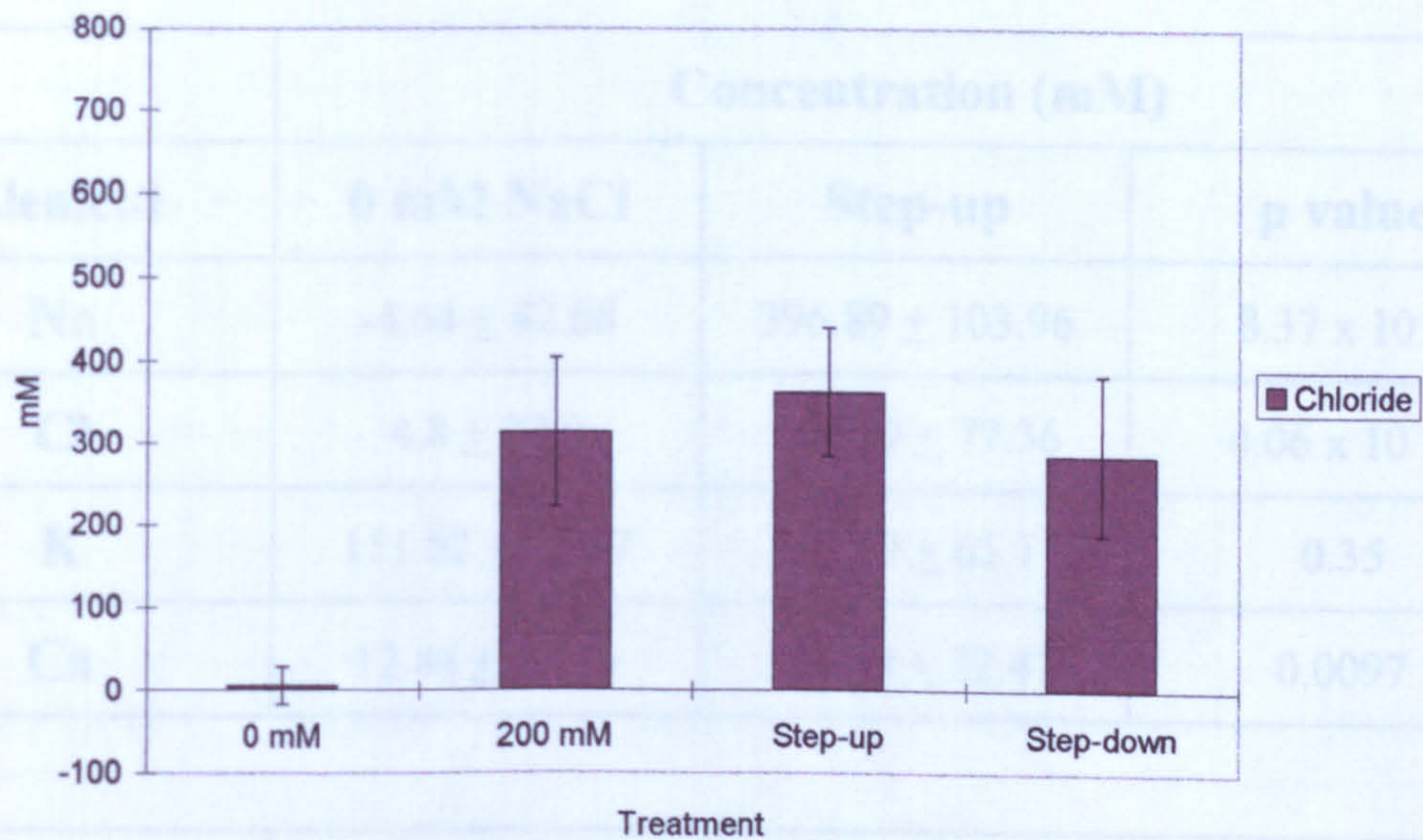
Mean sodium concentration in leaf epidermal sap samples taken from control and 24 hour step-up/step-down treated *Suaeda maritima* plants at day 14 (leaf pair 1 and 2). Error bars indicate standard deviation, n is 15 cells (5 plant, 3 cells per plant). The statistical analysis tool used was a paired t-Test. The p values generated for 0 mM/step-up and 200 mM/step-down treatments were  $8.37 \times 10^{-9}$  and 0.045 respectively.





**Figure 3.9, Chloride concentration in leaf epidermal sap samples taken from *Suaeda maritima* plants 24 hours after a step-up/step-down treatment**

Mean chloride concentration in leaf epidermal sap samples taken from control and 24 hour step-up/step-down treated *Suaeda maritima* plants at day 14 (leaf pair 1 and 2). Error bars indicate standard deviation, n is 15 cells (5 plant, 3 cells per plant). The statistical analysis tool used was a paired t-Test. The p values generated for 0 mM/step-up and 200 mM/step-down treatments were  $4.06 \times 10^{-11}$  and 0.38 respectively.



Element	200 mM NaCl	Step-down	p value
Na	159.3 ± 170.35	424.04 ± 135.61	0.045
Cl	313.12 ± 50.61	285.54 ± 97.63	0.38
K	29.91 ± 25.74	69.51 ± 34.89	0.042
Ca	25.15 ± 10.11	25.01 ± 14.12	0.0009



**Table 3.3, EDX analysis of sodium, chloride, potassium and calcium in leaf epidermal sap samples in control and 24 hour step-up/step-down *Suaeda maritima* plants at day 14**

Sodium, chloride, potassium and calcium concentrations in leaf epidermal sap samples taken from control and 24 hour step-up\step-down treated *Suaeda maritima* plants at day 14 (leaf pair 1 and 2). Data are presented as mean and standard deviation, n is 15 cells (5 plants, 3 cells per plant). The statistical analysis tool used was a paired t-Test.

Element	Concentration (mM)		
	0 mM NaCl	Step-up	p value
Na	$-4.64 \pm 42.68$	$396.89 \pm 103.96$	$8.37 \times 10^{-9}$
Cl	$4.8 \pm 22.9$	$361.79 \pm 77.36$	$4.06 \times 10^{-11}$
K	$151.52 \pm 58.97$	$131.39 \pm 61.11$	0.35
Ca	$12.84 \pm 23.35$	$-11.89 \pm 22.47$	0.0097

Element	Concentration (mM)		
	200 mM NaCl	Step-down	p value
Na	$563.3 \pm 170.56$	$424.04 \pm 135.61$	0.045
Cl	$313.02 \pm 90.61$	$285.54 \pm 97.63$	0.38
K	$29.41 \pm 25.74$	$69.51 \pm 34.89$	0.042
Ca	$-5.15 \pm 10.11$	$-25.01 \pm 14.12$	0.0009



**Table 3.4, The relationship between osmotic pressure ( $\Pi_{\text{cell}}$ ) and solute concentration in individual *Suaeda maritima* leaf epidermal cells**

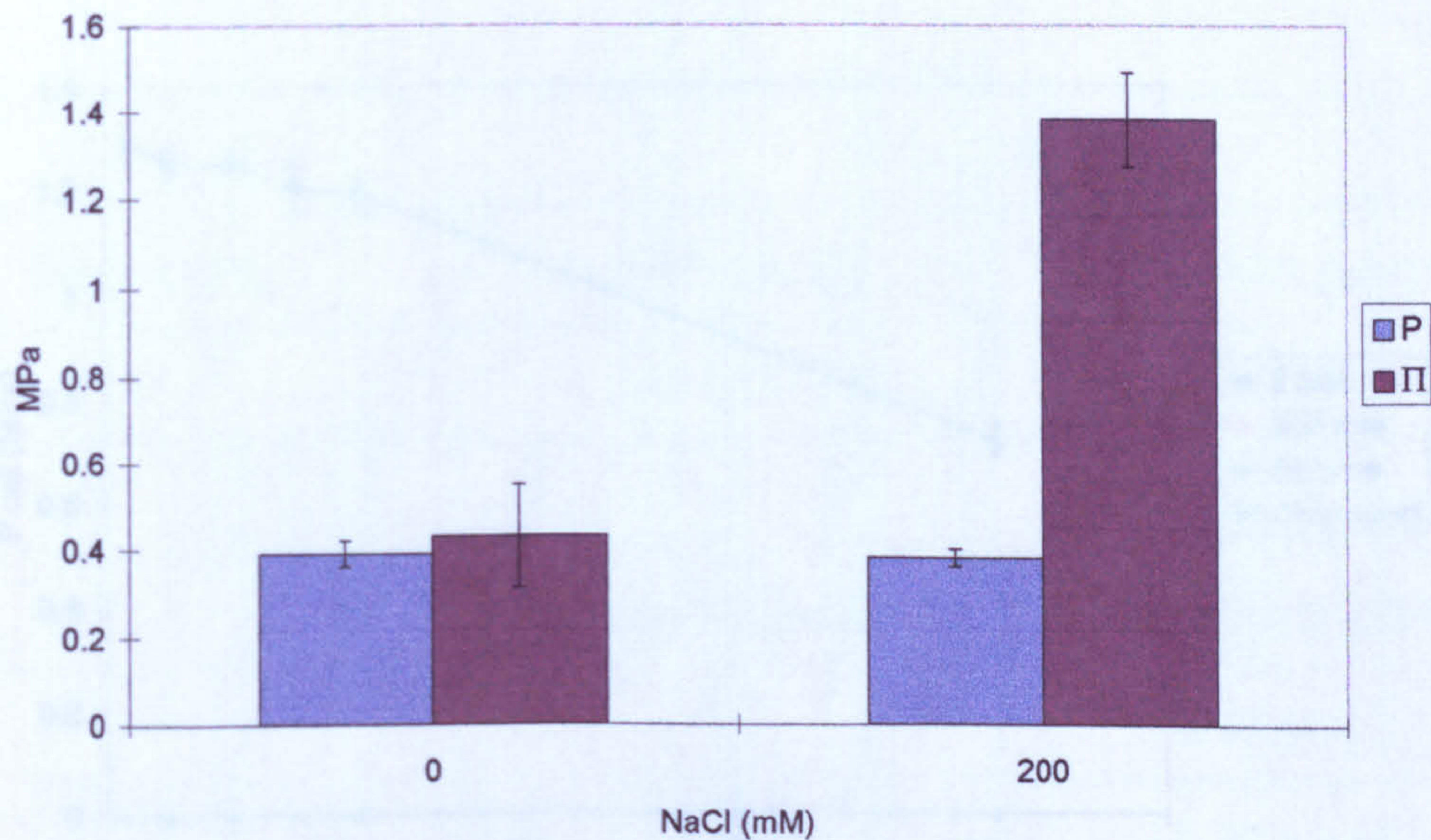
The relationship between the molarity of solutes measured by EDX X-ray microanalysis and osmolality measured by picolitre melting point depression in the same sap sample. Calculated  $\Pi_{\text{cell}}$  values correspond to the sum of EDX measured solutes (mM) multiplied by an osmotic coefficient of 0.82 (after Fricke *et al.*, 1994).

	<b>NaCl Treatment</b>			
<b>Solute (mM)</b>	<b>0 mM</b>	<b>200 mM</b>	<b>Step-up</b>	<b>Step-down</b>
<b>Na</b>	0	563.3	396.89	424.04
<b>Cl</b>	4.8	313.02	361.79	285.54
<b>K</b>	151.52	29.41	131.39	69.51
<b>Ca</b>	12.84	0	0	0
<b>Sum of solutes</b>	<b>169.16</b>	<b>905.73</b>	<b>890.07</b>	<b>779.09</b>
<b>Osmolality mOsmol kg<sup>-1</sup></b>				
<b>Measured <math>\Pi_{\text{cell}}</math></b>	568	1,032	984	948
<b>Calculated <math>\Pi_{\text{cell}}</math></b>	138.7	846.24	729.86	638.85
<b>Difference</b>	<b>429.3</b>	<b>185.76</b>	<b>254.14</b>	<b>309.15</b>



**Figure 3.10,  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  in *Suaeda maritima* root cortex cells at day 21**

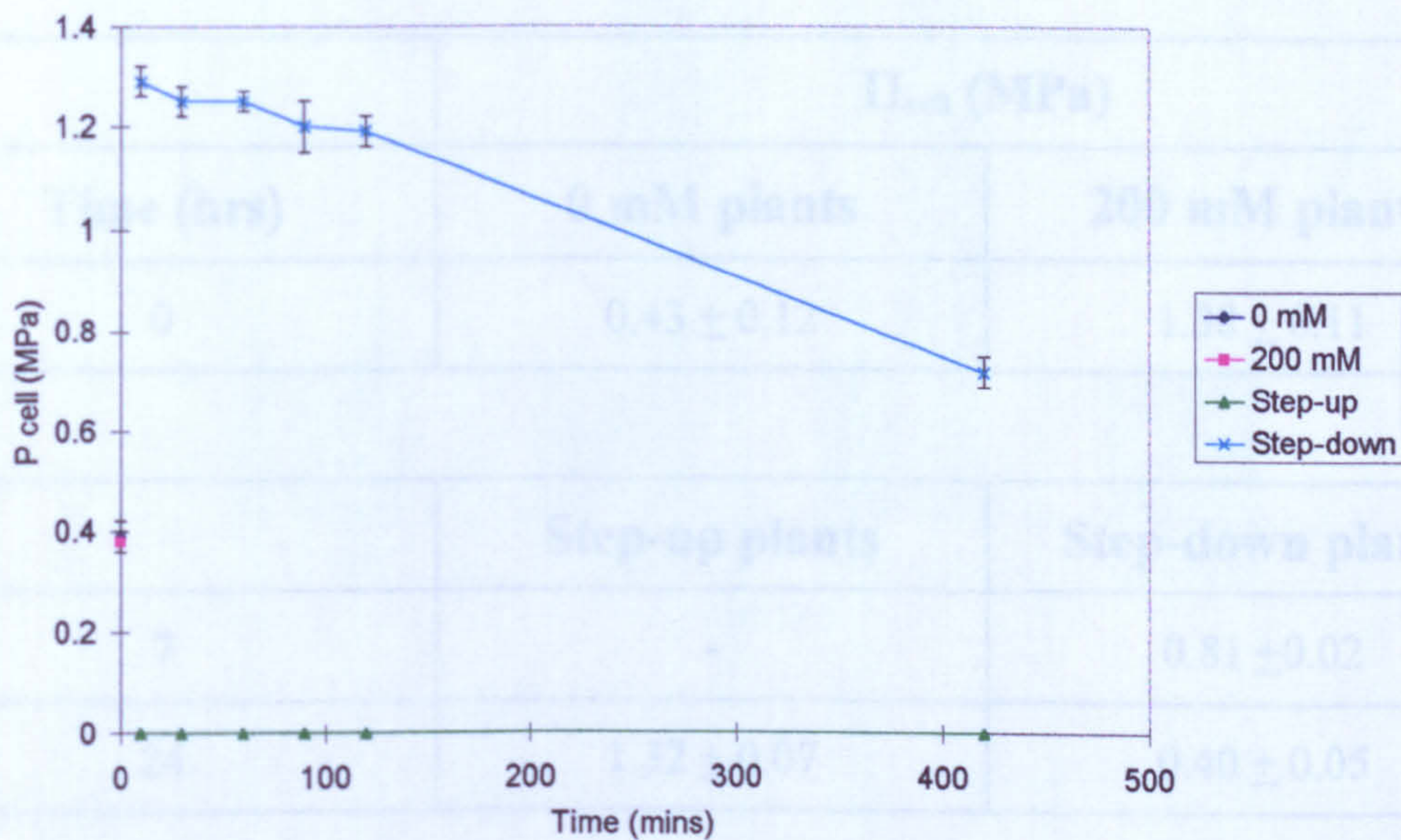
Mean turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in root cortex cells (1 cm from the root tip) at day 21. The error bars indicate standard deviation,  $P_{\text{cell}}$  n is 15 cells (5 plants, 3 cells per plant),  $\Pi_{\text{cell}}$  n = 15 plants (sap from 5 cells pooled per plant). The statistical analysis tool used was a paired t-Test. The  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  p values generated were 0.51 and  $9.2 \times 10^{-9}$  respectively.





**Figure 3.11, Root cortex  $P_{\text{cell}}$  in *Suaeda maritima* plants subjected to a step-up/step-down treatment**

Mean root cortex turgor pressure ( $P_{\text{cell}}$ ) in *Suaeda maritima* plants subjected to a step-up or step-down of 1 MPa in the external medium at day 21 (measurements were made 1 cm from the root tip).  $P_{\text{cell}}$  measurements were taken prior to treatment (Time 0) and at the times indicated after treatment. The error bars indicate standard deviation, n is 15 root cortex cell (5 plants, 3 cells per plant).





**Table 3.5, Root cortex  $\Pi_{\text{cell}}$  in *Suaeda maritima* plants subjected to a step-up/step-down treatment**

Root cortex osmotic pressure ( $\Pi_{\text{cell}}$ ) in *Suaeda maritima* plants subjected to a step-up or step-down of 1 MPa in the external medium at day 21 (measurements were made 1 cm from the root tip).  $\Pi_{\text{cell}}$  measurements were taken prior to treatment (Time 0) and at the times indicated after treatment. Data are presented as mean and standard deviation, n is 15 plants (sap from 5 cells pooled per plant). A dash (-) signifies inability to obtain a cell sample due to plasmolysis.

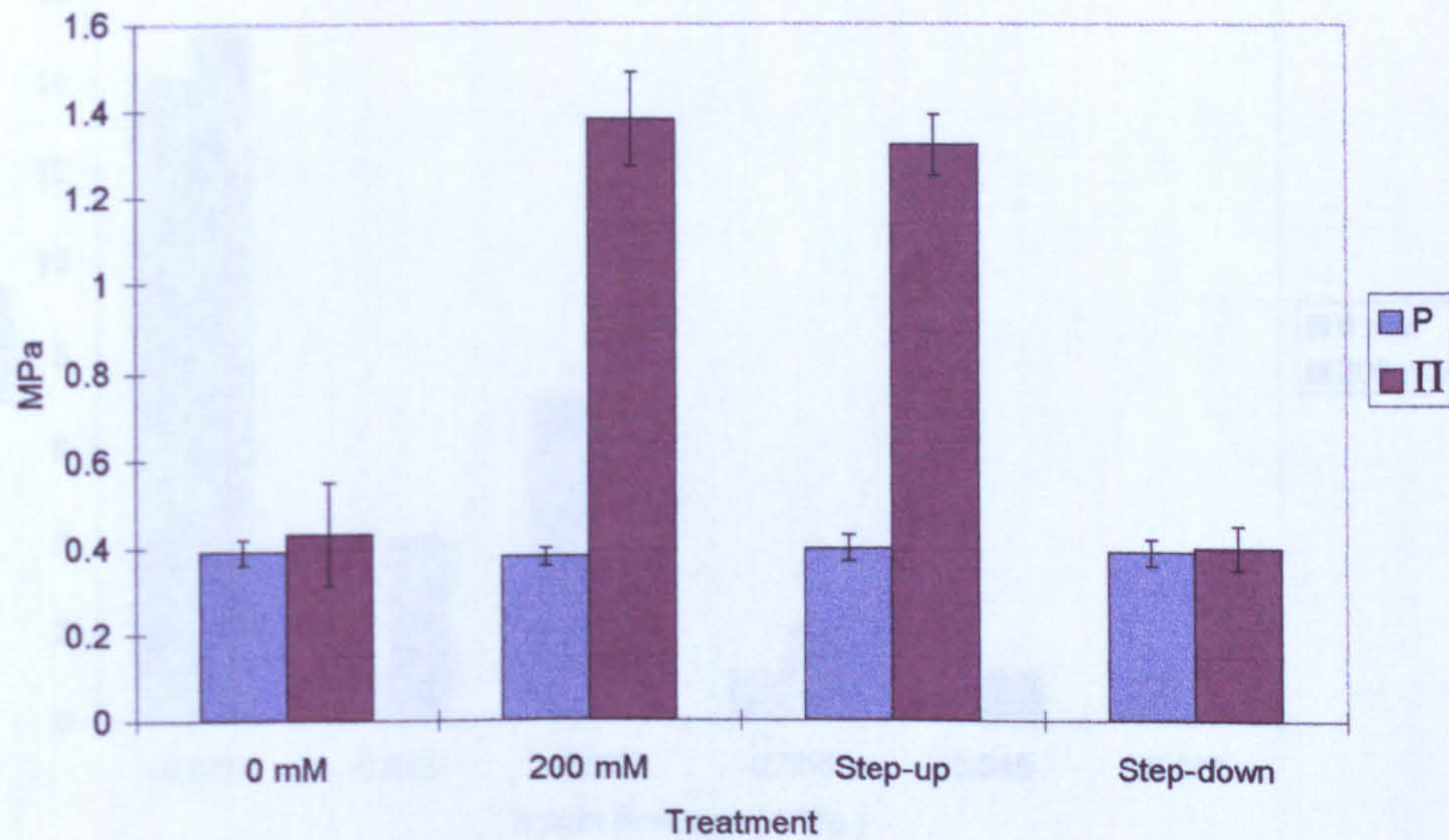
Time (hrs)	$\Pi_{\text{cell}}$ (MPa)	
	0 mM plants	200 mM plants
0	0.43 $\pm$ 0.12	1.38 $\pm$ 0.11

	Step-up plants	Step-down plants
7	-	0.81 $\pm$ 0.02
24	1.32 $\pm$ 0.07	0.40 $\pm$ 0.05



**Figure 3.12,  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  in *Suaeda maritima* root cortex cells 24 hours after a step-up/step-down treatment**

Mean turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in *Suaeda maritima* root cortex cells 24 hours after a step-up/step-down treatment (day 21, 1 cm from the root tip). Error bars indicate standard deviation, n is 15 plants (sap from 5 cells pooled per plant).



**Figure 3.14, Distribution of turgor pressure ( $P_{\text{cell}}$ ) in *Suaeda maritima* stems at day 21**

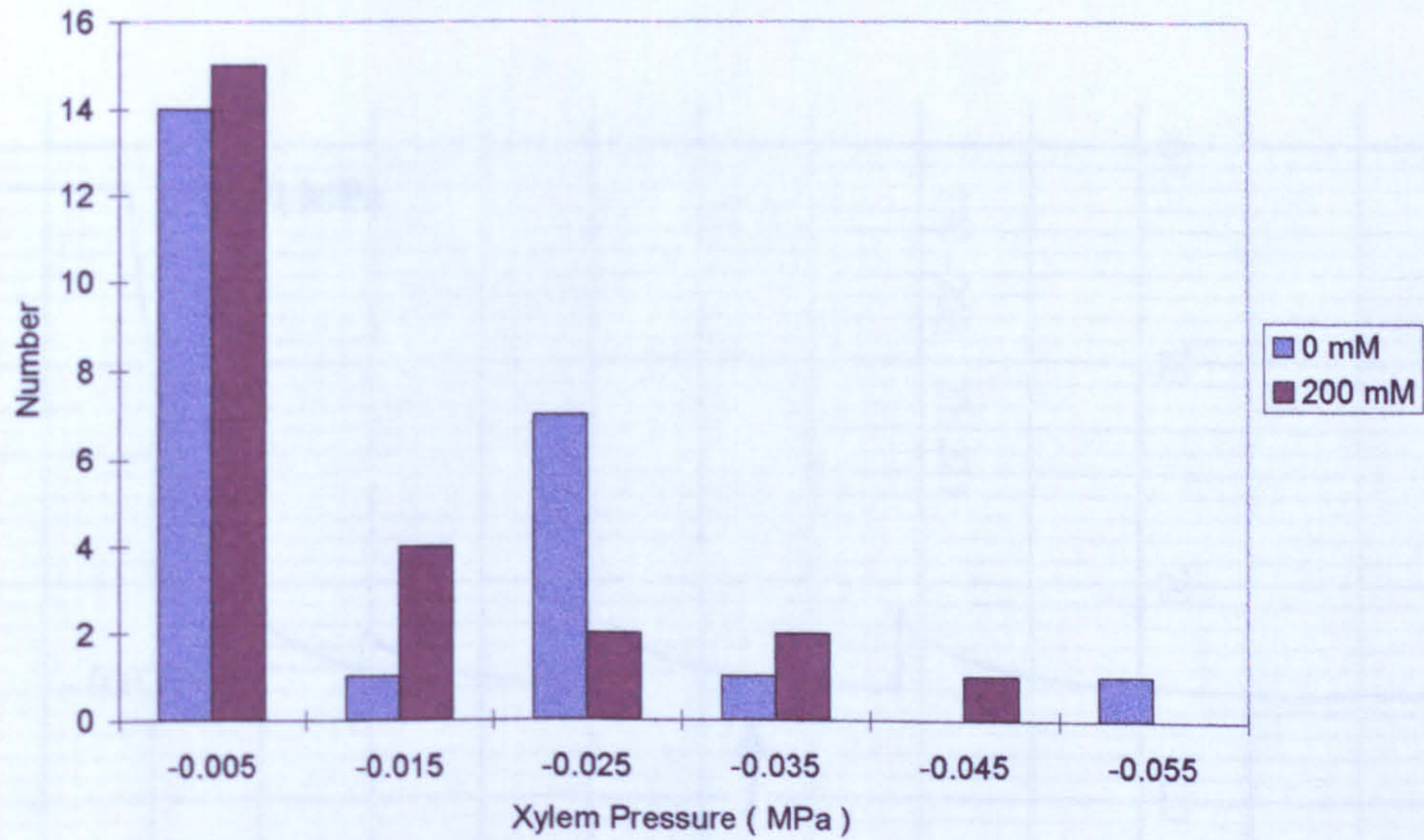
Distribution of turgor pressure ( $P_{\text{cell}}$ ) in the stem of *Suaeda maritima* plants grown in 0 mM and 200 mM NaCl at day 21. The data have been grouped together to form a frequency distribution chart, n = 15 plants.





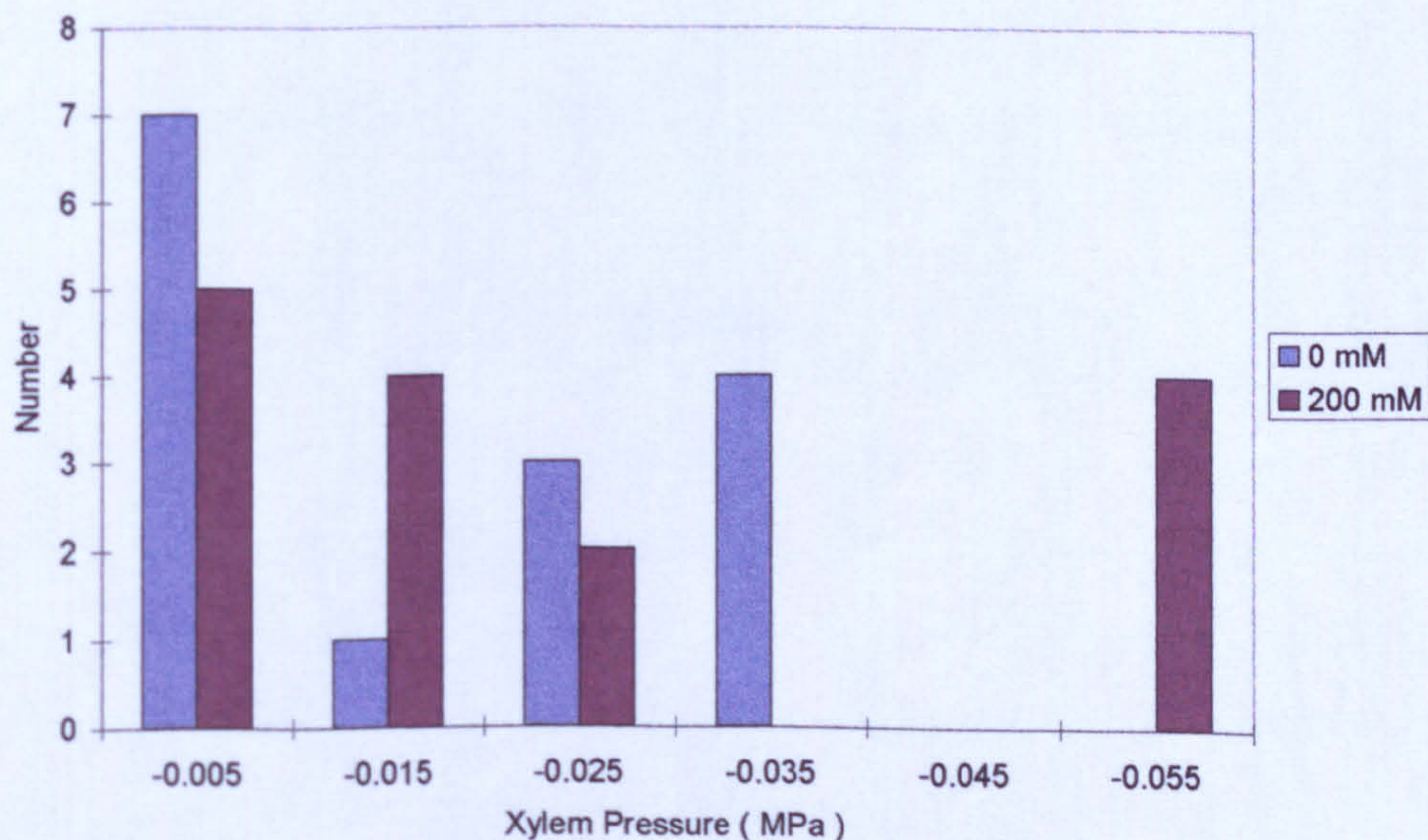
**Figure 3.13, Distribution of xylem pressure ( $P_{\text{xylem}}$ ) in *Suaeda maritima* stems at day 14**

Distribution of xylem pressure ( $P_{\text{xylem}}$ ) in the stem of *Suaeda maritima* plants grown in 0 mM and 200 mM NaCl at day 14. The data have been grouped together to form a frequency distribution chart, n is 25 plants.



**Figure 3.14, Distribution of xylem pressure ( $P_{\text{xylem}}$ ) in *Suaeda maritima* stems at day 21**

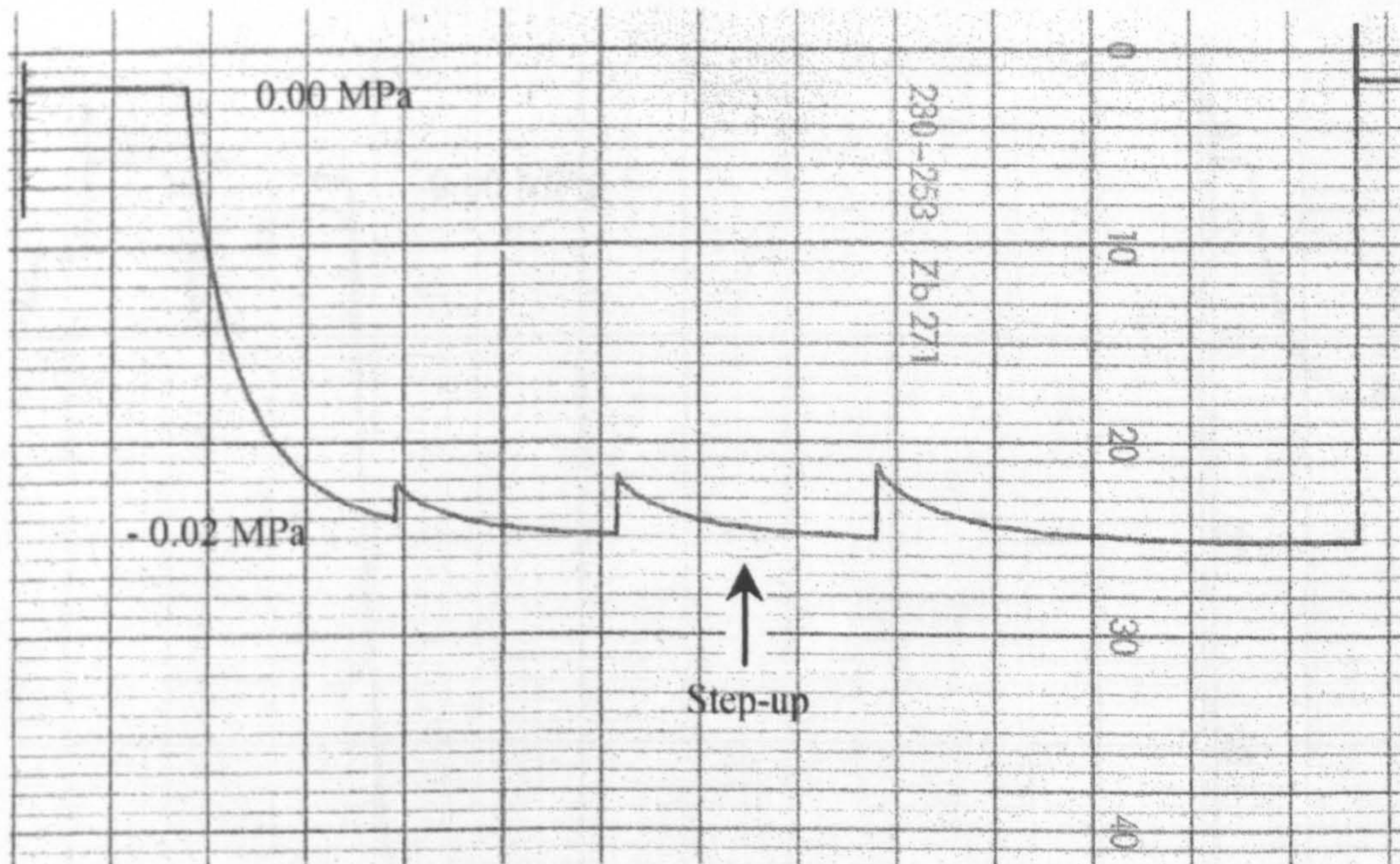
Distribution of xylem pressure ( $P_{\text{xylem}}$ ) in the stem of *Suaeda maritima* plants grown in 0 mM and 200 mM NaCl at day 21. The data have been grouped together to form a frequency distribution chart, n = 15 plants.





**Figure 3.15, Xylem pressure ( $P_{\text{xylem}}$ ) in a *Suaeda maritima* stem before and after a step-up treatment at day 21**

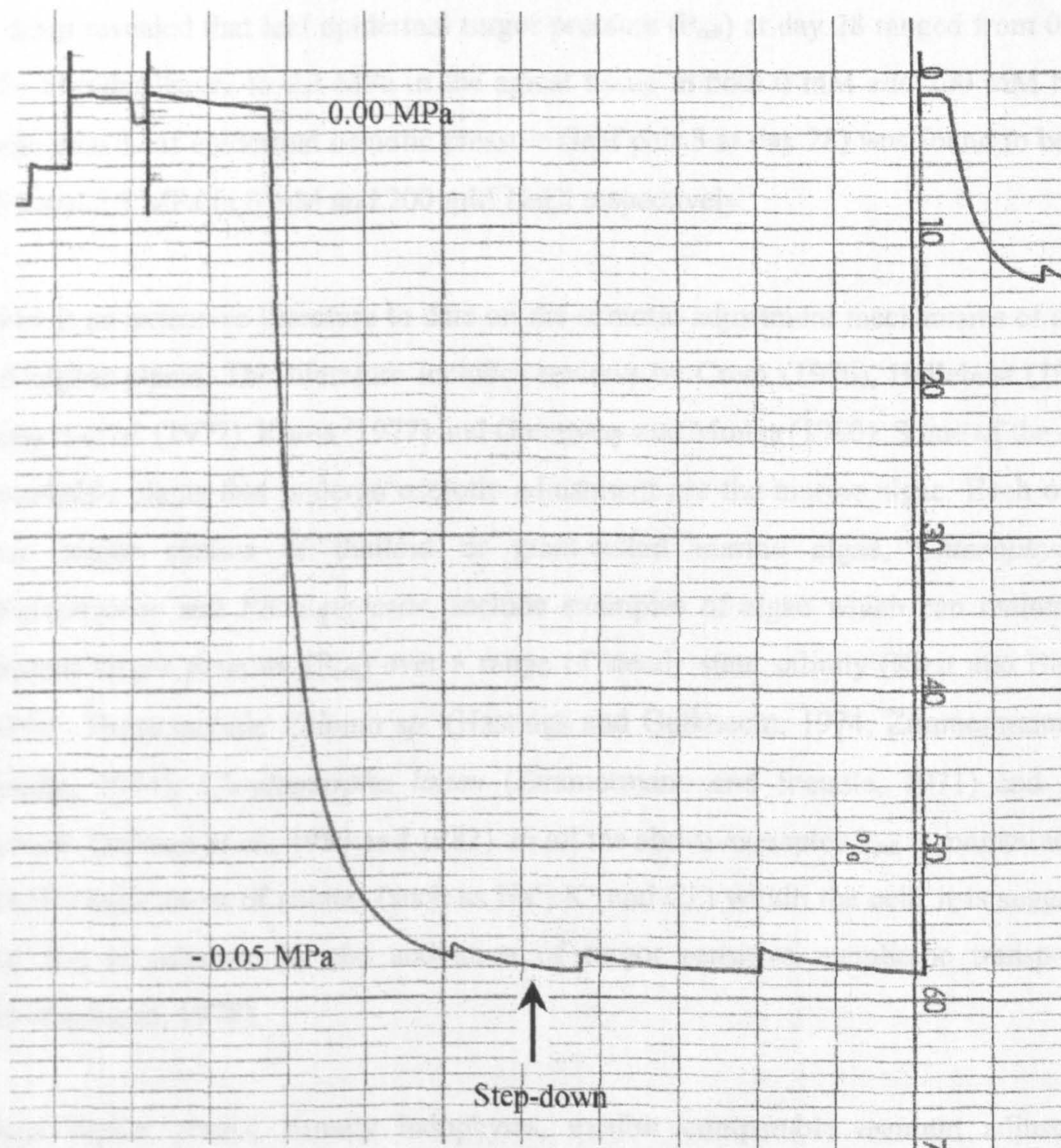
A single xylem pressure trace obtained from the stem of a 0 mM NaCl *Suaeda maritima* plant at day 21. The arrow indicates the point at which a 1 MPa step-up treatment was applied to the root system. The peaks indicate pressure pulses applied manually to the xylem probe system. The chart recorder speed was set at  $10 \text{ mm min}^{-1}$ . Each division on the horizontal axis is equivalent to 1 cm.





**Figure 3.16, Xylem pressure ( $P_{\text{xylem}}$ ) in a *Suaeda maritima* stem before and after a step-down treatment at day 21**

A single xylem pressure trace obtained from the stem of a 200 mM NaCl *Suaeda maritima* plant at day 21. The arrow indicates the point at which a 1 MPa step-down treatment was applied to the root system. The peaks indicate pressure pulses applied manually to the xylem probe system. The chart recorder speed was set at 10 mm min<sup>-1</sup>. Each division on the horizontal axis is equivalent to 1 cm.





### 3.4, Discussion

#### 3.4.1, *Suaeda maritima* leaf epidermal cells

In this chapter, data is presented which demonstrates that *Suaeda maritima* plants grown in steady state 0 mM and 200 mM NaCl regimes, regulate leaf epidermal turgor pressure and undergo complete osmotic adjustment in relation to the external medium. These data are in agreement with the work carried out by Clipson *et al.* in 1985. Their findings revealed that leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) at day 28 ranged from 0.025 MPa in older leaves to 0.3 MPa in the apical tissue in both 0 mM and 200 mM NaCl treatments. Leaf epidermal osmotic pressure (leaf pair 3 at day 28) was found to be 1.5 MPa and 2.5 MPa in 0 mM and 200 mM NaCl respectively.

There is an extensive literature to date on the osmotic adjustment mechanisms of algae and higher plants. The literature includes reviews by Cram (1976), Hellebust (1976), Flowers *et al.* (1977), Kauss (1977) and Greenway and Munns (1980). Some of the most remarkable plants that undergo osmotic adjustment are the marine algae. Each of the three major classes of thalloid or giant-celled marine algae, *Chlorophyceae*, *Rhodophyceae* and *Phaeophyceae*, include examples of algae which can maintain a constant turgor pressure ( $P_{\text{cell}}$ ) over a range of steady state salinity (Kirst and Bisson, 1979). These include *Valonia sp.* (Hastings and Gutknecht, 1974; Zimmermann and Steudle, 1974), *Chaetomorpha linum* (Zimmermann and Steudle, 1971) and *Ulva lactuca* (Dickson *et al.*, 1980 and 1982). In all the above examples  $P_{\text{cell}}$  is maintained by osmotic adjustment of solutes (such as  $\text{Na}^+$ ,  $\text{K}^+$  and  $\text{Cl}^-$ ) within the cell; it is suggested that this is achieved by the activation of turgor sensitive membrane transporters (Zimmermann, 1978).

Many higher plants, namely halophytes, exhibit comparable osmotic adjustment mechanisms. An increase in external osmotic pressure ( $\Pi_{\text{ext}}$ ) often leads to the accumulation of solutes in the shoot and root. Examples include, *Salicornia bigelovii* (Stumpf and O'Leary, 1985), *Thinopyrum bessarabicum* (Gorham *et al.*, 1985), *Suaeda maritima* (this chapter, Clipson *et al.*, 1985; Reimann, 1992), *Atriplex prostrata* (Reimann, 1992) and *Atriplex canescens* (Glenn *et al.*, 1996). *Suaeda maritima* plants



in a steady state NaCl environment have leaf epidermal osmotic pressures ( $\Pi_{\text{cell}}$ ) which reflect the osmotic pressure of the external medium (this chapter and Clipson *et al.*, 1985). Accumulation of solutes induced by an increase in  $\Pi_{\text{ext}}$  enables a plant to maintain a water potential which is lower than that of the external medium, and thus facilitate the uptake of water into the plant. Halophytes exhibit a wide range of osmotic pressures which are often considerably higher than those found in glycophytes (Cram, 1976; Flowers, 1975). Salt marsh species such as *Spartina glabra*, *Juncus gerardii*, *Salicornia bigelovii* and *Atriplex hasta* have whole plant osmotic pressures of 3.5 MPa, 4.0 MPa, 4.9 MPa and 3.2 MPa respectively (Steiner, 1934). Tropical mangrove species such as *Sonnerata alba* and *Avicennia marina* have leaf osmotic pressures ranging from 3.3 MPa to 3.5 MPa and 3.5 MPa to 6.2 MPa respectively (Field, 1984 {a} and {b}).

Even in a highly dilute hydroponic medium (in the absence of NaCl) *Suaeda maritima* accumulates a high level of solutes in the leaf epidermal cells (this chapter and Clipson *et al.*, 1985). This is in fact characteristic of many halophytes. Walter (1962) found that halophytes grown in a dilute hydroponic medium had osmotic pressures which were approximately double those of comparable glycophytes grown in the same growth medium. This high constitutive capacity for ion uptake may be a mechanism employed by halophytes in preparation for a sudden increase in external osmotic pressure ( $\Pi_{\text{ext}}$ ). *Suaeda maritima* plants grown in 0 mM NaCl accumulate solutes to what appears to be a predetermined baseline level. When NaCl is included in the external medium the osmotic pressure of the leaf epidermal cells ( $\Pi_{\text{cell}}$ ) is equal to the cell baseline plus the osmotic pressure of the external medium (this chapter, Clipson *et al.*, 1985). From the data presented in this chapter the baseline leaf epidermal cell osmotic pressure is between 1.2 - 1.4 MPa. Plants grown in a 1 MPa NaCl medium (200 mM NaCl) have a cell osmotic pressure of 2.2 - 2.4 MPa, which is equivalent to the baseline plus  $\Pi_{\text{ext}}$ . Full osmotic adjustment takes place despite the fact that the baseline osmotic pressure is greater than the osmotic pressure of the 200 mM NaCl medium.

The magnitude of the osmotic pressure in *Suaeda maritima* leaf epidermal cells is not reflected by the turgor pressure (this chapter and Clipson *et al.*, 1985). Clipson *et al.* (1985) demonstrated that the leaf epidermal turgor pressure in *Suaeda maritima* ranged



from 0.025 MPa in older leaves to 0.3 MPa in the apical tissue. The turgor pressure measurements described in this chapter were on leaves approaching full expansion; the leaf epidermal  $P_{\text{cell}}$  values obtained were around 0.2 MPa. Compared with other species *Suaeda maritima* has a low leaf epidermal turgor pressure; for example, the salt tolerant alga *Chara longifolia* has a turgor pressure of 0.55 MPa (Bisson *et al.*, 1995) whereas, *Tradescantia virginiana* and *Triticum aestivum* have leaf epidermal turgor pressures of 0.45 MPa (Tomos *et al.*, 1981) and 0.85 MPa (Bates, 1998) respectively.

The reason why *Suaeda maritima* regulates leaf epidermal turgor pressure to such a low level is unclear, however, how such a regulation is achieved can be explained. Assuming that the reflection coefficient ( $\sigma$ ) of a cell is close to unity, turgor pressure ( $P_{\text{cell}}$ ) can be influenced by the osmotic pressure of the cell ( $\Pi_{\text{cell}}$ ), the osmotic pressure of the apoplast ( $\Pi_{\text{wall}}$ ) and by the hydrostatic component of the apoplast, which is the transpiration tension ( $P_{\text{wall}}$ ). This relationship can be expressed very simply in the following equation:

$$P_{\text{cell}} = (\Pi_{\text{cell}} - \Pi_{\text{wall}}) - P_{\text{wall}}$$

Assuming the reflection coefficient is 1, any difference between cell turgor pressure ( $P_{\text{cell}}$ ) and cell osmotic pressure ( $\Pi_{\text{cell}}$ ) can only be due to the osmotic ( $\Pi_{\text{wall}}$ ) and/or hydrostatic ( $P_{\text{wall}}$ ) components of the apoplast (cell wall). The influence of  $P_{\text{wall}}$  on cell turgor pressure can be measured directly by measuring turgor pressure in transpiring and non-transpiring leaves. I have shown that eliminating transpiration does not affect  $P_{\text{cell}}$  in *Suaeda maritima* plants at day 14; by day 21, however, a 0.1 MPa increase in  $P_{\text{cell}}$  is observed in non-transpiring plants. Clipson *et al.* (1985) reported similar findings; *Suaeda maritima* plants immersed in hydroponic solution for several hours had a leaf epidermal  $P_{\text{cell}}$  which was 0.1 MPa - 0.2 MPa greater than  $P_{\text{cell}}$  in freely transpiring control plants, at day 28. The increase in  $P_{\text{cell}}$  observed in older non-transpiring plants points to an increased transpiration rate which is likely to be due to an increase in leaf size and number. These data indicate that the hydrostatic component of the apoplast



exerts only a small influence on cell turgor pressure (compared to the magnitude of the difference between  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$ ). The difference between  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  is a massive 1.2 MPa and 2.2 MPa in 0 mM and 200 mM NaCl plants respectively (this chapter). Even if the hydrostatic component of the wall accounts for 0.1 MPa of this difference, the bulk of the difference is still unaccounted for. This leads to the conclusion that the difference between turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in *Suaeda maritima* leaf epidermal cells is largely due to the presence of solutes in the apoplast ( $\Pi_{\text{wall}}$ ). X-ray microanalyses of thin sections of leaf tissue in *Suaeda maritima* plants grown in steady state 340 mM NaCl, revealed that the apoplast surrounding the mesophyll had  $\text{Na}^+$  and  $\text{Cl}^-$  concentrations, based on apoplastic water content, of up to 550 mM and 400 mM respectively (Flowers, 1985). This is equivalent to a wall osmotic pressure of approximately 2.4 MPa. It is necessary to point out here that this method cannot distinguish between free wall solutes and Donnan bound solutes which do not exert a net osmotic effect (Tomos, 1988; Nobel, 1991).

Analysis of the solutes present in the apoplast of other species has revealed that glycophytes have a relatively low concentration of solutes in the apoplast. For example, Jachetta *et al.* (1986) analysed aliquots of sap expressed from detached sunflower leaves in a pressure chamber over intervals of 0.02 - 0.04 MPa. Three distinct fractions were successively released, a petiole/midrib fraction, a minor vein/cell wall fraction and a mixed fraction. Analysis (by vapour pressure osmometry) of the minor vein/cell wall fraction revealed that mature sunflower leaves have an apoplastic osmotic pressure ( $\Pi_{\text{wall}}$ ) of 0.05 MPa. Nonami and Boyer (1987) applied a 0.03 - 0.04 MPa pressure to the roots of soybean and pea seedlings, using a pressure chamber. Under saturating humidity this resulted in droplets of exudate forming on the elongating region of the intact stem. This exudate was assumed to be apoplastic in nature and analysis, using a micro-osmometer (based on the thermocouple psychrometer described by Boyer and Knipling in 1965), revealed that the enlarging region of soybean and pea seedling stems have  $\Pi_{\text{wall}}$  values of 0.041 MPa and 0.028 MPa respectively. Meinzer and Moore (1988) collected apoplastic samples from sugarcane leaf segments (3.5 cm long, cut at different distances from the shoot apex) by centrifugation of noninfiltrated tissue. The osmotic pressure of the apoplastic sample was determined using a vapour pressure osmometer.



Apoplastic osmotic pressure ( $\Pi_{\text{wall}}$ ) values ranged from 0.25 MPa to 0.35 MPa depending on the physiological age of the leaves; fully mature leaves having the lower apoplastic solute content.

Accumulation of solutes in the apoplast is often associated with salt stress (Oertli, 1968; O'Toole and Cruz, 1979; Flowers *et al.*, 1991). Rice cultivars exhibit leaf rolling in response to external salinity (O'Toole and Cruze, 1979; Flowers *et al.*, 1991). The leaf rolling phenomenon is believed to be induced by loss of water from the cells due to an excessive and undesirable accumulation of solutes (namely  $\text{Na}^+$  and  $\text{Cl}^-$ ) in the apoplast. Flowers *et al.* (1991) measured sodium plus potassium concentrations in the leaf apoplast of two rice cultivars (IR 2153 and Amber) grown in 50 mM NaCl for 9 days. This was achieved by X-ray microanalysis of thin transverse sections (1 - 3 mm thick) taken from the middle of the lamina of the second and third leaf. Sodium plus potassium concentrations of up to 511 mM (IR 2153) and 840 mM (Amber) were observed. This high extracellular accumulation of solutes is uncontrolled and believed to be a primary factor in salinity damage in these plants. In contrast, the high concentration of solutes present in the apoplast of *Suaeda maritima* leaf epidermal cells does not induce damage and would appear to play an important part in turgor pressure regulation (this chapter).

Steady state NaCl experiments have attracted criticism in the past from marine zoologists (for example, Stickle and Ahokas, 1974; Davenport *et al.*, 1975) because they do not reflect field conditions. In a salt marsh environment salinity levels can fluctuate wildly due to tidal inundation, evapo-transpiration, fresh water input and rainfall (Jefferies *et al.*, 1983). In this chapter, I describe an experimental regime designed to subject *Suaeda maritima* plants to a rapid step-up or step-down of 1 MPa in the hydroponic medium. *Suaeda maritima* plants grown initially in 0 mM NaCl were placed in a medium containing 200 mM NaCl (step-up), whereas plants grown initially in 200 mM NaCl were placed in a hydroponic medium which did not contain NaCl (step-down). Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) measurements taken immediately after a step-up/step-down treatment revealed that  $P_{\text{cell}}$  was completely unaffected by a 1 MPa up or down osmotic shock. Measurements were taken for up to 2 hours after treatment;  $P_{\text{cell}}$  was maintained at around 0.2 MPa throughout. This is in contrast to the



situation observed in marine algae. *Ulva lactuca* undergoes short term changes in turgor pressure ( $P_{\text{cell}}$ ) in response to changes in external salinity; turgor pressure is restored by long term osmotic adjustment mechanisms over a number of hours (Dickson *et al.*, 1982). The marine alga *Cladophora rupestris* also experiences changes in  $P_{\text{cell}}$  due to changes in external salinity, but in this case complete osmotic adjustment leading to turgor regulation is not achieved (Wiencke *et al.*, 1991).

The leaf epidermal cells in *Suaeda maritima* are not in direct contact with the external medium, as is the case with the marine algae, and as a result can be buffered against the immediate effects of rapid changes in salinity (the possible nature of this buffering mechanism will be discussed later). Having such a mechanism in place is likely to facilitate protoplasmic osmotic adjustment. By maintaining leaf turgor pressure, transpiration can continue (loss of leaf cell turgor pressure would interrupt the transpiration stream and inhibit the transport of inorganic solutes to the shoot via the xylem - Marschner, 1995). A 1 MPa increase in external NaCl (from 0 mM to 200 mM NaCl) depresses the transpiration rate in *Suaeda maritima* by only 25 % after 6 hours. Subsequent recovery to 95 % of the control values is achieved within 24 hours (Clipson, 1987). Preservation of the transpiration stream in a fluctuating NaCl environment facilitates the transport of inorganic solutes from root to shoot, thus providing the solutes necessary for osmotic adjustment in the shoot, and preventing the build up of  $\text{Na}^+$  and  $\text{Cl}^-$  to toxic levels in the root cortex (Clipson, 1987).

After 24 hours in the step-up/step-down treatments leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) remained unchanged. Changes were observed, however, in leaf epidermal osmotic pressure ( $\Pi_{\text{cell}}$ ). *Suaeda maritima* step-up plants accumulated solutes in the leaf epidermal cells, leading to an increase in cell osmotic pressure which corresponded to the increase applied to the external medium, which was 1 MPa. Step-down plants, on the other hand, did not mobilise solutes out of the leaf epidermal cells,  $\Pi_{\text{cell}}$  was maintained despite the 1 MPa decrease in the external medium ( $\Pi_{\text{ext}}$ ). In other words, *Suaeda maritima* leaf epidermal cells readily accumulate solutes, over 24 hours, in response to an increase in external NaCl. However, a decrease in external NaCl does not induce mobilisation of solutes out of the cell; this results in a massive difference



between the cell osmotic pressure ( $\Pi_{\text{cell}}$ ) and the osmotic pressure of the external medium ( $\Pi_{\text{ext}}$ ).

EDX analysis confirmed that the solutes accumulated in the leaf epidermal cell vacuoles of *Suaeda maritima* plants grown in steady state and step-up NaCl media were indeed largely  $\text{Na}^+$  and  $\text{Cl}^-$ . The accumulated  $\text{Na}^+$  and  $\text{Cl}^-$  easily accounts for the increased cell osmotic pressure ( $\Pi_{\text{cell}}$ ) observed in these plants. Step-up plants, for example, accumulated 397 mM and 357 mM  $\text{Na}^+$  and  $\text{Cl}^-$  respectively within 24 hours (this chapter). Taking into account the osmotic coefficient, the sum of these solutes should give rise to an increase in  $\Pi_{\text{cell}}$  of 1.5 MPa. Plants grown in the absence of NaCl had negligible amounts of  $\text{Na}^+$  and  $\text{Cl}^-$  in the cell vacuoles; the main solute present was apparently potassium (this chapter).

Clipson (1987) also presented data which demonstrates that an NaCl step-up leads to an increase in shoot solute accumulation. *Suaeda maritima* plants grown in 0 mM and 200 mM NaCl media were subjected to a 1 MPa step-up 14 days after transfer to hydroponics (28 days after germination). In common with the experiments described in this chapter, the NaCl concentration was increased in a single step. Plants given a step-up from 0 mM to 200 mM NaCl increased cotyledon  $\Pi_{\text{cell}}$  from 1.3 MPa to 2.9 MPa, and plants given a step-up from 200 mM to 400 mM NaCl increased apical  $\Pi_{\text{cell}}$  from 2.0 MPa to 3.0 MPa respectively. Most leaves reached a new steady state osmotic pressure ( $\Pi_{\text{cell}}$ ) within 24 hours. Osmotic pressure was determined by dew point hygrometry (as described in Clipson *et al.*, 1985).

Clipson (1987) took the step-up experiment a stage further and measured the rate of sodium accumulation in the shoot and the rate of sodium transport from root to shoot. Clipson's findings revealed that shoot  $\text{Na}^+$  accumulation and  $\text{Na}^+$  transport rates increased markedly in plants subjected to a step-up from 2 mM to 202 mM NaCl. During the first 6 hours of the step-up treatment the rate of accumulation in the shoot, and the root to shoot transport rate increased from 3 to 80  $\mu\text{mol Na}^+ \text{g}^{-1} \text{DWS h}^{-1}$  and 10 to 370  $\mu\text{mol Na}^+ (\text{shoot}) \text{g}^{-1} \text{DWR h}^{-1}$  respectively.



In summary, an increase in external NaCl concentration leads to complete osmotic adjustment of *Suaeda maritima* leaf epidermal cells within 24 hours (this chapter and Clipson, 1987). The solutes utilised for osmotic adjustment purposes are Na<sup>+</sup> and Cl<sup>-</sup> (this chapter and Clipson, 1987). Accumulation of solutes into the cells is facilitated by an increase in root to shoot transport rate (Clipson, 1987).

Examples of other halophytes which accumulate high levels of Na<sup>+</sup> and Cl<sup>-</sup> in the leaves in response to an increase in external NaCl include *Atriplex hasta* (Black, 1956), *Suaeda monoica* (Storey and Wyn Jones, 1979) and *Avicennia marina* (Downton, 1982). Each of these species accumulate Na<sup>+</sup> and Cl<sup>-</sup> in the leaves to a level which exceeds the concentration in the external medium. For example, *Atriplex hasta* plants grown in media containing 100 mM and 400 mM NaCl were found to have leaf Na<sup>+</sup> concentrations of 658 mM and 1203 mM respectively, and Cl<sup>-</sup> concentrations of 430 mM and 911 mM respectively (Black, 1956; Flowers, 1985).

Bacteria also accumulate high concentrations of ions within the cell, particularly potassium (Csonka, 1989; Csonka and Hanson, 1991). Some specialised halophytic bacteria possess enzymes which are only active *in vitro* in ion concentrations that are inhibitory to similar enzymes extracted from less tolerant organisms (Larsen, 1967; Peterkin and Fitt, 1971). In addition, high levels of K<sup>+</sup> and Mg<sup>2+</sup> are required for the stability of their ribosomes (Bayley and Kushner, 1964), indicating that a high ion content is necessary for protein synthesis.

In plants, the situation is quite different. Brady *et al.* (1984) assessed the stability of ribosomes incubated in NaCl and KCl solutions at 25 °C. The ribosomes were recovered from a number of plant species, including, *Triticum aestivum*, *Hordeum vulgare*, *Capsicum annum*, *Helianthus annus*, *Pisum savitum*, *Beta vulgaris*, *Chenopodium album*, *Atriplex nummularia*, *Ulva lactuca*, *Enteromorpha intestinalis*, *Cladophora* sp., and *Corallina cuvieri*. Their findings revealed that plant ribosomal systems, in both halophytic and glycophytic species, are unstable in media containing 250 mM NaCl or KCl. In *Suaeda maritima*, 100 mM Na<sup>+</sup> in the cytoplasm reduces ribosomal activity by 50 % (Hall and Flowers, 1973). Furthermore, enzymes isolated from halophytic plant species are inhibited by concentrations of NaCl which also inhibit comparable enzymes



in salt sensitive species (Flowers, 1972 {a} and {b}; Greenway and Osmond, 1972; Flowers *et al.*, 1976; Wyn Jones *et al.*, 1977 {a} and {b}; Wyn Jones *et al.*, 1979; Wyn Jones and Pollard, 1983). Flowers (1972 {b}) studied the effect of NaCl on enzymes from 4 halophytic species from the family *Chenopodiaceae*; *Salicornia ramosissima*, *Suaeda maritima*, *Halimione portulacoides* and the maritime sub-species of *Beta vulgaris*. Flowers found that, in general, enzymes isolated from these species were just as sensitive to NaCl as enzymes isolated from the highly salt sensitive plant *Pisum sativum* (Flowers, 1972 {a} and {b}). Therefore, in order to tolerate high levels of NaCl in the cell, halophytes such as *Suaeda maritima* must minimise the build up of Na<sup>+</sup> and Cl<sup>-</sup> ions at the sites of active metabolic activity, namely the cytoplasm.

Using efflux, or compartmental analysis techniques, Yeo (1981) demonstrated that accumulated Na<sup>+</sup> in *Suaeda maritima* leaves is sequestered in the cell vacuoles. The concentration of Na<sup>+</sup> in the cytoplasm of *Suaeda maritima* leaf cells was estimated to be 165 mM (Yeo, 1981), whereas the concentration in the vacuole was between 500 mM - 600 mM (this chapter; Yeo, 1981; Yeo and Flowers, 1986). Evidence of Cl<sup>-</sup> compartmentation has been published by Harvey *et al.* (1976). This was achieved by silver precipitation and electron microscopy, and is a qualitative rather than a quantitative method.

Due to the Na<sup>+</sup> electrochemical gradient, Na<sup>+</sup> influx across the plasma membrane and into the cytoplasm is likely to be a passive process (Niu *et al.*, 1995). The exact mechanism of Na<sup>+</sup> influx is unknown. The uptake of Na<sup>+</sup> depresses K<sup>+</sup> influx (Wataid *et al.*, 1991; Schroeder *et al.*, 1994), suggesting that the uptake mechanisms for these ions may be similar. Efflux of Na<sup>+</sup> out of the cytoplasm, across the plasma membrane and tonoplast is an active process believed to be facilitated by an Na<sup>+</sup>/H<sup>+</sup> antiport driven by a pH gradient generated by the plasma membrane P-type and tonoplast V-type proton ATPase respectively (Niu *et al.*, 1995). Plasma membrane Na<sup>+</sup>/H<sup>+</sup> antiport activity has been stimulated by NaCl in the marine alga *Dunaliella salina* (Katz *et al.*, 1992) and the halophyte *Atriplex nummularia* (Hassidim *et al.*, 1990). Tonoplast Na<sup>+</sup>/H<sup>+</sup> antiport activity increases in response to elevated NaCl concentrations in the halophyte *Mesembryanthemum crystallinum* (Barkla *et al.*, 1995), *Beta vulgaris* (Blumwald and



Poole, 1985), sunflower roots (Ballesteros *et al.*, 1997), barley roots (Garbarino and DuPont, 1988), and tobacco culture cells (Reuveni *et al.*, 1990).

Once NaCl has been sequestered in the leaf cell vacuole it is not easily remobilised out of the cell. This is observed in leaf epidermal cells of *Suaeda maritima* plants subjected to a step-down NaCl treatment (this chapter). Maathuis *et al.* (1992) suggested that ions are prevented from re-entering the cytoplasm by a very low gating frequency of non-specific slow vacuolar (SV) channels (as described by Hedrich *et al.*, 1988; Maathuis and Prins, 1990) in the tonoplast.

An osmotic balance is maintained between the vacuole and cytoplasm in *Suaeda maritima* by accumulation of  $K^+$  and the compatible solute glycinebetaine in the cytoplasm (Wyn Jones, 1981; Gorham and Wyn Jones, 1983).

### 3.4.2, *Suaeda maritima* root cortex cells

In steady state 0 mM and 200 mM NaCl growth media, *Suaeda maritima* root cortex turgor pressure ( $P_{cell}$ ) is maintained at a constant level (around 0.4 MPa). The root cortex osmotic pressure ( $\Pi_{cell}$ ) in plants grown in the 0 mM NaCl medium corresponds exactly with the cell turgor pressure. Plants grown in the 1 MPa NaCl medium (200 mM NaCl plants) have a root cortex  $\Pi_{cell}$  which is 1 MPa greater than in plants grown in the absence of NaCl (this chapter). In other words, *Suaeda maritima* root cortex cells can regulate turgor pressure ( $P_{cell}$ ) over a range of steady state NaCl concentrations and undergo complete osmotic adjustment in relation to the external medium. Under steady state conditions the root cortex cells behave in a similar fashion to the leaf epidermal cells discussed earlier (see Section 3.4.1), however, there are notable differences between the two cell types. The high constitutive capacity for ion uptake, in a dilute medium, in *Suaeda maritima* leaf epidermal cells, is not observed in the root cortex cells. Also, the apoplast surrounding the root cortex cells cannot be utilised as a useful osmotic compartment.



In order for a cell to exert any kind of control over the apoplast, the apoplastic compartment must be closed to the external medium. The apoplast of the root cortex cells is probably completely open to the external medium, and as a result effectively occupies the same volume as the external medium. This would make manipulation of the apoplastic compartment extremely difficult and metabolically expensive. In this case the properties of the apoplast can be considered to be the same as the properties of the external medium. Assuming a reflection coefficient of 1, turgor pressure ( $P_{\text{cell}}$ ) can now be determined by simply subtracting the osmotic pressure of the external medium ( $\Pi_{\text{ext}}$ ) from the osmotic pressure of the cell ( $\Pi_{\text{cell}}$ ). This is illustrated in the equation below:

$$P_{\text{cell}} = \Pi_{\text{cell}} - \Pi_{\text{ext}}$$

The response of *Suaeda maritima* root cortex cells to rapid fluctuations in NaCl is very different to that observed in the leaf epidermal cells; at least in the short term. Root cortex cells subjected to a 1 MPa step-up, from 0 mM to 200 mM NaCl, experienced a rapid drop in cell turgor, and cell plasmolysis well within 10 minutes, whereas root cortex cells given a 1 MPa step-down, from 200 mM to 0 mM NaCl, underwent an equally rapid and dramatic increase in cell turgor pressure (this chapter). The root cortex cells were acting as perfect osmometers (Cram, 1976), undergoing changes in turgor pressure ( $P_{\text{cell}}$ ) which mirror the changes in external osmotic pressure ( $\Pi_{\text{ext}}$ ). Turgor pressure regulation took place by means of osmotic adjustment of solutes within the cell over a number of hours (this chapter). A decrease in root cortex turgor pressure ( $P_{\text{cell}}$ ) in step-down treated plants was observed within 30 minutes,  $P_{\text{cell}}$  decreased by 0.5 MPa within 7 hours reaching 0.8 MPa; just over half way to the complete osmotic adjustment  $P_{\text{cell}}$  target of 0.4 MPa. The decrease in  $P_{\text{cell}}$  was accompanied by a corresponding decrease in osmotic pressure ( $\Pi_{\text{cell}}$ ). Root cortex  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  were both approximately 0.8 MPa 7 hours after application of the step-down treatment. No turgor regulation was observed in the step-up treated plants at this stage. This may be due to the fact that the step-up treatment induced cell plasmolysis, which due to the severe nature of plasmolysis may inhibit the membrane transport mechanisms necessary to achieve osmotic adjustment.



Within 24 hours osmotic adjustment leading to turgor regulation was complete. Root cortex turgor pressure ( $P_{\text{cell}}$ ) had been restored and was comparable to control levels in both step-up and step-down treated *Suaeda maritima* plants. Root cortex osmotic pressure ( $\Pi_{\text{cell}}$ ) in step-up plants increased by 1 MPa, whereas  $\Pi_{\text{cell}}$  in step-down plants decreased by 1 MPa; exactly mirroring the changes in the external medium ( $\Pi_{\text{ext}}$ ). These data demonstrate that *Suaeda maritima* root cortex cells freely accumulate solutes in response to an increase in external NaCl and also freely mobilise solutes out of the cell in response to a decrease in external NaCl. This is a text book example of osmotic adjustment, and is comparable to the osmotic adjustment mechanism observed in the marine alga *Ulva lactuca* (Dickson *et al.*, 1980 and 1982).

*Suaeda maritima* leaf epidermal cells also freely accumulate solutes in response to an increase in external NaCl (this chapter), but as I discussed earlier in Section 3.4.1, these accumulated solutes are not remobilised out of the cell in response to a decrease in external NaCl, and are effectively trapped in the leaf epidermal vacuoles due to the properties of the tonoplast. In the root cortex the situation is somewhat different, and solutes are readily mobilised out of the cells. It is believed that remobilised solutes are preferentially transported to the shoot in order to maintain an adequate water potential gradient from root to shoot (Stelter and Jeschke, 1983; Storey *et al.*, 1983; Pitman, 1984; Yeo and Flowers, 1986). It has been calculated that more than 80% of the total sodium content of *Suaeda maritima* is found in the leaves (Pitman, 1984). Preferential transport of solutes from root to shoot has also been observed in the halophyte *Atriplex prostrata* (Reimann, 1992). In contrast, *Chenopodium album* and *Chenopodium schraderianum* (which belong to the same family as *Suaeda* and *Atriplex*; the *Chenopodiaceae*) have low  $\text{Na}^+$  and  $\text{Cl}^-$  concentrations in the shoot and much higher concentrations in the root; this is due to a low transport rate from root to shoot, and is an example of NaCl exclusion (Reimann, 1992).

### 3.4.3, *Suaeda maritima* xylem pressure ( $P_{\text{xylem}}$ ) in the stem

The stem xylem pressure values obtained in *Suaeda maritima* plants grown in steady state 0 mM and 200 mM NaCl ranged from -0.005 MPa to -0.055 MPa in both cases.



The majority of the values obtained were around -0.005 MPa, although  $P_{\text{xylem}}$  values of a greater magnitude were obtained more frequently in the older plants, at day 21 (all xylem pressure data is expressed relative to atmospheric pressure). By day 21 *Suaeda maritima* seedlings are considerably larger than they were at day 14. Leaf surface area has increased and up to 4 new leaf pairs have emerged (data not shown). This results in an increase in transpiration rate (as discussed in Section 3.4.1), which subsequently leads to an increase in xylem tension in the stem (see Benkert *et al.*, 1995; Zimmermann *et al.*, 1995). At day 21 the transpiration tension ( $P_{\text{wall}}$ ) in the apoplast adjacent to the leaf epidermal cells was approximately -0.1 MPa, whereas the xylem tension ( $P_{\text{xylem}}$ ) in the stem was between -0.005 MPa and -0.055 MPa (this chapter). The difference in hydrostatic tension values in the leaf apoplast and stem xylem provide evidence of a negative pressure gradient along the axis of the plant.

The large pressure gradients predicted by the original Cohesion Theory (Dixon and Joly, 1894 and 1895) appear to be unnecessary to achieve xylem flux. Zimmermann and co-workers have demonstrated that tension in the xylem is much lower than that required by the cohesion theory (see Zimmermann *et al.*, 1993; Zimmermann *et al.*, 1994 {a}). In light of this, Martin Canny (1995) proposed a new theory for the ascent of sap, which involves cohesion supported by tissue pressure. **The Compensating Pressure Theory** proposes that the driving force for the ascent of sap is provided by evaporation of water from the leaves, and the tensions generated in the curved menisci in the wet cell walls of the leaf. This force is transmitted by tension in the water in the tracheary elements. Thus far the new theory is in agreement with the original Cohesion Theory. However, Canny's theory goes on to suggest that this tension is kept within the cavitation threshold by compression induced by tissue pressure around the tracheary elements. This theory eliminates the need for a large axial tension gradient to sustain sap flow, however it is conceded that smaller tension gradients are necessary to overcome the resistance to water flow in the xylem and apoplast. The xylem conduits are of relatively large diameter compared to the capillaries which exist in the walls between cells. The xylem system therefore offers a pathway of low resistance to the flow of water relative to the cell walls (Nobel, 1991; Malone, 1993). Water flux through a cylinder is defined by the Hagen- Poiseuille law (see Nobel, 1991).



In order to determine whether fluctuations in external NaCl led to the propagation of a hydrostatic signal from root to shoot in *Suaeda maritima*, the xylem pressure probe was used to measure xylem pressure ( $P_{\text{xylem}}$ ) during a 1 MPa step-up/step-down treatment. Remarkably (given the dramatic response observed in the root cortex cells), the step-up/step-down treatment did not induce a detectable change in xylem pressure. This can possibly be explained in terms of root reflection coefficient and shoot transpiration rate.

Solute flux across a membrane can influence the flux of water across the same membrane. The relationship and interactions between solute and water fluxes have to be considered in estimating the rate of resultant osmotic flux. This is the role of the reflection coefficient ( $\sigma$ ). For a non-selective completely permeable membrane the reflection coefficient is 0, as there is no interaction between solute and water. If the membrane is permeable to water only, and completely impermeable to solutes (semipermeable), the reflection coefficient will be 1. Biological membranes, which are selectively-permeable, have reflection coefficient values ranging from 0 to 1, depending on the specific permeabilities for the different solutes and water (Dainty, 1963; Meidner and Sheriff, 1976; Nobel, 1991, Steudle, 1993). The radial reflection coefficient ( $\sigma_r$ ) of a root describes the properties of the barrier between the xylem compartment and the external medium. The radial reflection coefficient can be calculated using the following equation (assuming the root elastic modulus is equal to infinity):

$$\sigma_r = \Delta P_{\text{xylem}} / \Delta \Pi_{\text{ext}}$$

$\sigma_r$  = Radial reflection coefficient

$\Delta P_{\text{xylem}}$  = Change in xylem pressure

$\Delta \Pi_{\text{ext}}$  = Change in the osmotic pressure of the external medium



In the analysis of radial transport processes across roots, it has frequently been assumed that the root behaves like a perfect osmometer (Fiscus, 1977; Weatherly, 1982; Munns and Passioura, 1984). This implies that roots are completely semipermeable and have a radial reflection coefficient close to 1. There is evidence to suggest, however, that this is an over simplification. Steudle (1989, 1992 and 1993) carried out root pressure probe measurements on excised roots and found that the radial reflection coefficient was much lower (between 0.2 and 0.5). If this is indeed the case changes in xylem pressure ( $P_{\text{xylem}}$ ) due to changes in the external medium would be much less than expected for a perfect osmometer. It is important to consider, however, that data obtained from excised root tissue may not tell us a great deal about the properties of that tissue in the intact plant. The net water flow through an excised root is zero, whereas the intact root is a water transport system (Schneider *et al.*, 1997 {a} and {b}). Furthermore, the stationary turgor and osmotic pressure gradients in the cortex collapse when transpiration is eliminated by root excision (Rygor and Zimmermann, 1990; Zimmermann *et al.*, 1992; Rygor *et al.*, 1993; Clarkson, 1993). This leads to unpredictable changes in the distribution of osmotically active solutes, which subsequently results in concentration-polarisation effects in the root tissue. These concentration-polarisation effects are believed to influence water relations parameters such as the radial hydraulic conductivity as well as the radial and cellular reflection coefficients (Nobel, 1983; Barry and Diamond, 1984; Dainty, 1985).

The xylem pressure probe has been used to determine the root radial reflection coefficient in a number of intact plants, under various environmental conditions. The transpiration rate is believed to play a key role in determining the radial reflection coefficient of a root system (Zimmermann *et al.*, 1994 {b}; Schneider *et al.*, 1997 {a} and {b}). A high transpiration rate often results in a radial reflection coefficient which is close to 1. Whereas a low transpiration rate leads to much lower radial reflection coefficient values. Schneider *et al.* (1997 {a}) demonstrated that freely transpiring barley plants (in dry air) subjected to a 0.46 MPa step-up/step-down regime undergo changes in xylem pressure ( $P_{\text{xylem}}$ ) which correspond exactly with the changes in the external medium; in other words the root system behaves as a perfect osmometer when transpiration is maximised. For example, a 0.46 MPa step-up (from nutrient medium to



100 mM NaCl) resulted in a drop in  $P_{\text{xylem}}$  of 0.45 MPa within 10 minutes. This gives a root radial reflection coefficient of 0.98 for NaCl, as demonstrated below:

$$\sigma_r = \Delta P_{\text{xylem}} / \Delta \Pi_{\text{ext}}$$

$$\sigma_r = 0.45/0.46$$

$$\sigma_r = 0.98$$

Repeated nutrient medium/100 mM NaCl treatments revealed that the effect of NaCl on xylem pressure ( $P_{\text{xylem}}$ ) was reversible. The magnitude of the drop in  $P_{\text{xylem}}$  depended on the external NaCl concentration. The change in  $P_{\text{xylem}}$  equalled that expected for a perfect osmometer.

Comparable experiments were carried out on barley plants in which transpiration had been largely eliminated (in darkness and humidified air). The response of  $P_{\text{xylem}}$  to changes in  $\Pi_{\text{ext}}$  was greatly reduced under these conditions. Non-transpiring plants subjected to a step-up of 0.23 MPa underwent a drop in  $P_{\text{xylem}}$  of around 0.1 MPa, resulting in a radial reflection coefficient of 0.43 for NaCl. Similar findings were also observed in wheat (Schneider *et al.*, 1997 {a}).

Xylem pressure ( $P_{\text{xylem}}$ ) in the mangrove *Rhizophora mangle* does not respond to changes in NaCl concentration in the external medium. Plants transferred from tap water to a medium containing over 4.0 MPa NaCl maintained a constant  $P_{\text{xylem}}$  value (Zimmermann *et al.*, 1994 {b}). This corresponds to the *Suaeda maritima* xylem pressure data presented in this chapter. In conclusion, *Rhizophora mangle* and *Suaeda maritima* must have root radial reflection coefficients close to 0 for NaCl. This may be due to low transpiration rates in these plants. Low transpiration rates are often considered to be a characteristic feature of halophytes. The anatomy and physiology of many halophytes is geared towards reducing transpiration in order to minimise excessive and undesirable transport of solutes from root to shoot via the xylem (Flowers, 1985). Xylem pressure probe measurements have demonstrated that



*Rhizophora mangle* and *Suaeda maritima* do not maintain large negative xylem pressures in their xylem vessels. The xylem pressures measured in *Rhizophora mangle* and *Suaeda maritima* stems were largely + 0.05 MPa (absolute value - Zimmermann *et al.*, 1994 {b}) and - 0.005 MPa (relative to atmospheric pressure; this chapter) respectively. These low xylem tension values point to a low rate of transpiration in these plants (the relationship between transpiration rate and xylem pressure is discussed by Benkert *et al.*, 1991 and 1995). A root radial reflection coefficient which is 0 means that the effective osmotic pressure of the external medium is also 0, which may facilitate water uptake under conditions of fluctuating salinity.

Returning to the situation observed in *Suaeda maritima* root cortex cells (discussed in Section 3.4.2); the root cortex cells behave as perfect osmometers in response to changes in NaCl concentration in the external medium. Perfect osmometers are completely impermeable to solutes, in other words, a perfect osmometer has a permeability coefficient which is 0, and a reflection coefficient which is 1. However, the recent literature (see above) and the data presented in this chapter suggest that the root, as a whole, is not a perfect osmometer. The behaviour of a single cell or a single cell type cannot be equated with the behaviour of a whole tissue. The root cylinder is permeable to solutes, and as highlighted above, measurements on intact root systems have revealed that the radial reflection coefficient of a root is often less than 1. Transpiration appears to play an important role in determining the radial reflection coefficient (see above). However, other factors must also be taken into consideration including, root anatomy, the physiological age and development of the root, the pathways available for water and solute transport (apoplastic, symplastic and transcellular), the presence and number of water channels, and the number of such channels actively utilised at any one time. All the above parameters have been brought together by the **Composite Transport Model** (see Steudle and Peterson, 1998). This model describes the flux of water through a root, and allows for differences in water movement through individual cells as well as through various tissues (Steudle *et al.*, 1993; Steudle, 1994 {a} and {b}; Steudle and Frensch, 1996; Steudle and Peterson, 1998). The Composite Transport Model beautifully highlights the complexity and sophistication of the root system as a water transport device, and also reveals that we have much yet to learn.



The properties of the root system in *Suaeda maritima* also explains why the leaf epidermal cells do not respond to changes in NaCl concentration in the external medium (see Section 3.4.1). Due to the apparent low NaCl radial reflection coefficient of the root no hydrostatic signal is propagated from root to shoot via the xylem. As a result no immediate change in leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) would be expected.



## 3.5, Summary and conclusions

### 3.5.1, Leaf epidermal cells

- *Suaeda maritima* leaf epidermal cells maintain turgor pressure ( $P_{\text{cell}}$ ) at a level which is much lower than the osmotic pressure ( $\Pi_{\text{cell}}$ ) of the cell. Evidence suggests that this is achieved by the accumulation and adjustment of solutes in the adjacent apoplast ( $P_{\text{wall}}$ ). This indicates that *Suaeda maritima* utilises the apoplast as an osmotic compartment.
- A 1 MPa increase or decrease in external NaCl has no immediate or long term effect on leaf epidermal  $P_{\text{cell}}$ .
- *Suaeda maritima* leaf epidermal cells accumulate solutes (namely NaCl) in response to an increase in external salinity. The increase in cell osmotic pressure ( $\Pi_{\text{cell}}$ ) exactly mirrors the increase in external osmotic pressure ( $\Pi_{\text{ext}}$ ). Complete osmotic adjustment of the protoplast takes place within 24 hours.
- Solutes are not remobilised out of the leaf epidermal cells in response to a decrease in external salinity. This is believed to be due to the properties of the tonoplast in this cell type.

### 3.5.2, Root cortex cells

- Root cortex cells behave as perfect osmometers in response to fluctuations in  $\Pi_{\text{ext}}$ .
- The root cortex cells readily accumulate solutes in response to an increase in external NaCl. The increase in root cortex  $\Pi_{\text{cell}}$  exactly mirrors the increase in  $\Pi_{\text{ext}}$ . Osmotic adjustment of the protoplast is achieved within 24 hours.
- A decrease in external NaCl leads to mobilisation of solutes out of the cortex cells. The subsequent decrease in  $\Pi_{\text{cell}}$  exactly mirrors the decrease in  $\Pi_{\text{ext}}$ . The remobilised



solute are believed to be preferentially transported from the root to the shoot via the xylem. Once again, osmotic adjustment of the protoplast is achieved within 24 hours.

### 3.5.3, Xylem pressure/tension in the stem

- Xylem pressure ( $P_{\text{xylem}}$ ) can be measured successfully in *Suaeda maritima* stems using the xylem pressure probe.
- A 1 MPa NaCl increase or decrease in  $\Pi_{\text{ext}}$  does not lead to the propagation of a detectable hydrostatic signal from root to shoot via the xylem. This is believed to be due to the properties of the root as a whole and a root radial reflection coefficient which is close to 0.



## Chapter 4 : Turgor regulation by osmotic adjustment of apoplastic solutes in *Suaeda maritima* L. Dum. leaf epidermal cells

### 4.1, Introduction

The importance of apoplastic solutes in plant cell water relations has been highlighted by a number of authors, including: Leigh and Tomos (1983), Clipson *et al.* (1985), Tomos and Wyn Jones (1988), Tomos (1988), and Bell and Leigh (1996). Turgor regulation in beet taproot tissue is crucial, as high turgor pressure inhibits sucrose accumulation (Wyse *et al.*, 1986; Bell and Leigh, 1996). It is proposed that turgor regulation in red beet and sugar beet taproot tissue is achieved by apoplastic solute adjustment (namely apoplastic  $K^+$  - see Leigh and Tomos, 1983; Bell and Leigh, 1996). This would allow sucrose accumulation to continue while turgor pressure was maintained at a level which facilitates membrane transport (Leigh and Tomos, 1983; Tomos, 1988; Bell and Leigh, 1996; see also Chapter 5).

A comparable turgor regulation mechanism is believed to take place in *Suaeda maritima* leaf epidermal cells. In order to maintain water flux into the plant, *Suaeda maritima* must accumulate NaCl in the leaves in response to an increase in external NaCl (Flowers, 1975; Clipson *et al.*, 1985; see also Chapter 3). In the previous chapter (Chapter 3), I discussed data which clearly demonstrated that solutes were present in the apoplastic space adjacent to *Suaeda maritima* leaf epidermal cells. It was also clear that under a fluctuating external NaCl regime leaf epidermal turgor pressure could only be maintained if protoplasmic and apoplastic adjustment of solutes were taking place in parallel (see also Clipson *et al.*, 1985; Tomos and Wyn Jones, 1988).

This chapter describes a novel and exciting experimental protocol, which was first brought to our attention by Tomos and Wyn Jones (1988) in red beet taproot tissue. Turgor pressure in *Suaeda maritima* leaf epidermal cells is modulated by direct manipulation of the solutes present in the apoplast. Access to the apoplast is gained by slicing selected *Suaeda maritima* leaves open. The original apoplastic solutes are then washed out of the apoplast using a carefully selected osmoticum. After the washing



procedure is completed it is assumed that the only solutes left in the apoplast (at least initially) are those which were present in the osmoticum. At this stage the apoplast is either closed to the external environment using water saturated silicone oil or simply left open to the osmoticum. Turgor regulation and osmotic adjustment in the leaf epidermal cells is then monitored using the cell pressure probe and single cell sampling and analysis techniques (see **Chapter 2** and references therein). The beauty of this technique is that it allows one to access the apoplast and directly modulate the solute composition and apoplastic volume. This technique would also lend itself well to more detailed apoplastic solute flux studies using ion selective microelectrodes.



## 4.2, Method

### 4.2.1, Leaf selection and preparation

Leaves were excised from *Suaeda maritima* plants grown in 0 mM and 200 mM NaCl at day 14 (see Chapter 3, Section 3.2.1 for germination and hydroponic culture protocols), using a sharp pair of dissection scissors. Leaf selection was limited to leaf pair 1 and 2. The leaves were preferably undamaged and roughly symmetrical. The excised leaves were placed on a suitable cutting surface (such as a glass tile), adaxial side up, and cut longitudinally from end to end with a sharp double edged razor blade.

The sliced leaves were either used immediately or after pre-treatment in an osmoticum. Pre-treatment involved aerating the longitudinal leaf slices in 100 ml of osmoticum for 15 minutes. The following osmotica were used: 300 - 1000 mOsmoles kg<sup>-1</sup> NaCl and 400 - 900 mOsmoles kg<sup>-1</sup> melibiose (BDH). A single length of freshly cut or pre-treated leaf tissue was secured to a perspex sample holder. The tissue was immediately covered in 5 ml of water saturated silicone oil or a 5 ml aliquot of the aqueous osmoticum. Care was taken to ensure that the tissue was not exposed to the air for any length of time in order to prevent dehydration.

### 4.2.2, Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) measurement

The cells targeted with the pressure probe and sampling arm (see Chapter 2, Section 2.2 and 2.3) were leaf epidermal cells approximately 2 -3 cells away from the cut edge of the tissue. The cells situated at the extreme edge of the tissue were avoided due to the damage and stress caused by the cutting procedure.

Turgor pressure measurements were made, using the cell pressure probe (see Chapter 2, Section 2.2), at 5 minute intervals for a maximum of 90 minutes. Samples for picolitre osmometry (see Chapter 2, Section 2.5) were taken at 10 minute intervals for a maximum of 90 minutes. The time lag between applying the water saturated silicone oil to the tissue and taking the first measurements was kept to a minimum.



### 4.3, Results

Leaf epidermal cells at the cut edge of *Suaeda maritima* leaves - which have been sliced in half longitudinally and placed immediately under water saturated silicone oil - had a turgor pressure ( $P_{\text{cell}}$ ) which was initially too low to measure with the cell pressure probe (Figure 4.1 and 4.2). The act of slicing open a leaf invariably leads to cell damage. Solutes from the broken and damaged cells leach into the adjacent apoplastic space. This increase in apoplastic solute concentration leads to a decrease in turgor pressure of nearby, undamaged cells, as water is drawn out of the cells and into the apoplast. In order to determine whether the turgor pressure would recover over time, measurements were taken every 5 minutes for 90 minutes. Turgor pressure remained too low to measure successfully for approximately 15 minutes, after which time turgor pressure recovered steadily, reaching a plateau after 40 - 45 minutes. A steady turgor pressure of about 0.25 MPa was maintained for the duration of the experiment thereafter. This turgor pressure value is comparable with the leaf epidermal  $P_{\text{cell}}$  measurements obtained in corresponding leaves in intact *Suaeda maritima* plants (see Chapter 3, Figure 3.4). The selected leaves were taken from plants grown in 0 mM NaCl (Figure 4.1) and 200 mM NaCl (Figure 4.2) media; the turgor regulatory mechanism appeared to be identical for both (i.e. turgor regulation was achieved over the same time period in both 0 mM and 200 mM NaCl leaves).

The observed turgor regulation mechanism can be achieved either by adjustment of solutes within the protoplast or by adjustment of solutes in the apoplast. The time scale within which turgor regulation is achieved in these sliced leaves suggests that adjustment of the protoplast is unlikely; protoplasmic adjustment of solutes might be expected to take a number of hours rather than minutes (Cram, 1976). Leaf epidermal osmotic pressure ( $\Pi_{\text{cell}}$ ) measurements were taken from freshly sliced *Suaeda maritima* leaves under silicone oil in order to determine whether protoplasmic solute adjustment, leading to turgor regulation, was taking place (Figure 4.3 and 4.4). Leaf epidermal cells on leaf slices taken from *Suaeda maritima* plants grown in 0 mM and 200 mM NaCl had initial osmotic pressure ( $\Pi_{\text{cell}}$ ) values of approximately 1.4 MPa (Figure 4.3) and 2.4 MPa (Figure 4.4) respectively. This corresponds to the situation in the intact



plant (see Chapter 3, Figure 3.4). The 1 MPa difference between  $\Pi_{\text{cell}}$  in plants grown in 0 mM and 200 mM NaCl reflects the difference in the osmotic pressure of the external medium ( $\Pi_{\text{ext}}$ ). The time course of  $\Pi_{\text{cell}}$  measurements revealed that leaf epidermal osmotic pressure was maintained at initial values throughout the experiment. This leads to the conclusion that turgor regulation is most likely achieved by adjustment of solutes in the apoplast in this case.

In order better to understand the adjustment mechanism employed by *Suaeda maritima* leaf epidermal cells it was important to gain an element of control over the initial composition of the apoplastic compartment. The leaf apoplast adjacent to the cut face of the leaf slices was effectively completely open to the external environment prior to being covered with water saturated silicone oil. This allowed manipulation of the apoplastic compartment with carefully chosen aqueous osmotica. Aerating the leaf slices for 15 minutes in an osmoticum washed out the original apoplastic solutes and replaced them with those present in the osmoticum. While the leaf slices were in the aqueous media the apoplast effectively occupied the same volume as the osmoticum, which was 100 ml in this case; this is referred to as an open system. Once the pre-treatment was complete the leaf slices were covered in water saturated silicone oil which not only prevented dehydration of the leaf tissue, but also reduced the apoplastic volume to a level which mimics the apoplastic volume *in vivo*. As the silicone oil closes off the apoplast to the external environment, this system is referred to as a closed system (Tomos and Wyn Jones, 1988).

The osmotica contained either NaCl, which was assumed could be freely transported from apoplast to cell and vice versa, or melibiose, which is impermeant in nature and cannot cross the plasma membrane (Conner and Falloon, 1993). The osmotica were either more concentrated, less concentrated, or roughly equivalent to the estimated concentration of solutes present in the apoplast *in vivo*. The apoplastic concentration of solutes *in vivo* was estimated from the difference between turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in the leaf epidermal cells in intact *Suaeda maritima* plants under non-transpiring conditions (see Chapter 3, Figure 3.4 and Table 3.2).



*Suaeda maritima* leaf slices pre-treated in 600 mOsmoles kg<sup>-1</sup> NaCl (0 mM NaCl plants, **Figure 4.5**) and 1000 mOsmoles kg<sup>-1</sup> NaCl (200 mM NaCl plants, **Figure 4.6**) had initial leaf epidermal turgor pressures which were too low to be measured successfully. After 15 minutes turgor pressure had recovered sufficiently to be measured without undue difficulty. After 40 - 45 minutes  $P_{\text{cell}}$  reached a plateau at around 0.25 MPa, which was maintained at this level for the duration of the experiment. These data are comparable (most notably the final equilibrium  $P_{\text{cell}}$  values) to the data obtained from freshly sliced, untreated leaf tissue (**Figure 4.1 and 4.2**).

*Suaeda maritima* leaf slices pre-treated in less concentrated NaCl osmotica exhibited turgor regulation in the opposite direction. Leaf slices pre-treated in 300 mOsmoles kg<sup>-1</sup> NaCl (0 mM NaCl plants, **Figure 4.7**) and 600 mOsmoles kg<sup>-1</sup> NaCl (200 mM NaCl plants, **Figure 4.8**) had initial leaf epidermal turgor pressure values between 0.4 MPa and 0.45 MPa. Turgor pressure was regulated downwards almost immediately. Turgor pressure ( $P_{\text{cell}}$ ) levelled out again at between 0.2 MPa and 0.25 MPa within 30 - 35 minutes, and was maintained at this level for the duration of the experiment.

No change in leaf epidermal turgor pressure was observed in *Suaeda maritima* leaf slices pre-treated in NaCl osmotica with an intermediate solute concentration. This suggests that the solute concentration in the osmoticum is comparable to the concentration of solutes in the leaf apoplast solution *in vivo*. Leaf slices pre-treated in 400 mOsmoles kg<sup>-1</sup> NaCl (0 mM NaCl plants, **Figure 4.9**) and 800 mOsmoles kg<sup>-1</sup> NaCl (200 mM NaCl plants, **Figure 4.10**) maintained turgor pressure ( $P_{\text{cell}}$ ) at just over 0.2 MPa throughout the experiment. Note that this level of turgor pressure ( $P_{\text{cell}}$ ) corresponds to leaf epidermal  $P_{\text{cell}}$  in the intact plant, and also corresponds to the target  $P_{\text{cell}}$  level achieved by the upward and downward turgor regulation mechanisms observed in **Figure 4.5 and 4.6**, and **Figure 4.7 and 4.8** respectively.

A control experiment was carried out to determine whether this turgor regulation phenomenon could also be observed in the open system environment. *Suaeda maritima* leaf slices were aerated in 500 mOsmoles kg<sup>-1</sup> NaCl (0 mM NaCl plants, **Figure 4.11**) and 900 mOsmoles kg<sup>-1</sup> NaCl (200 mM NaCl plants, **Figure 4.12**) for 15 minutes. After



pre-treatment the leaf slices were not covered in silicone oil, but rather in a 5 ml aliquot of the bathing osmoticum. Turgor pressure ( $P_{\text{cell}}$ ) measurements were taken at 5 minute intervals for 90 minutes. The osmotica induced a decrease in leaf epidermal turgor pressure. However, turgor pressure was not regulated upwards and was maintained at the initial level of between 0.075 MPa - 0.1 MPa for the duration of the experiment. This indicates that the volume of the apoplast is key to the turgor regulatory mechanism in *Suaeda maritima* leaf epidermal cells.

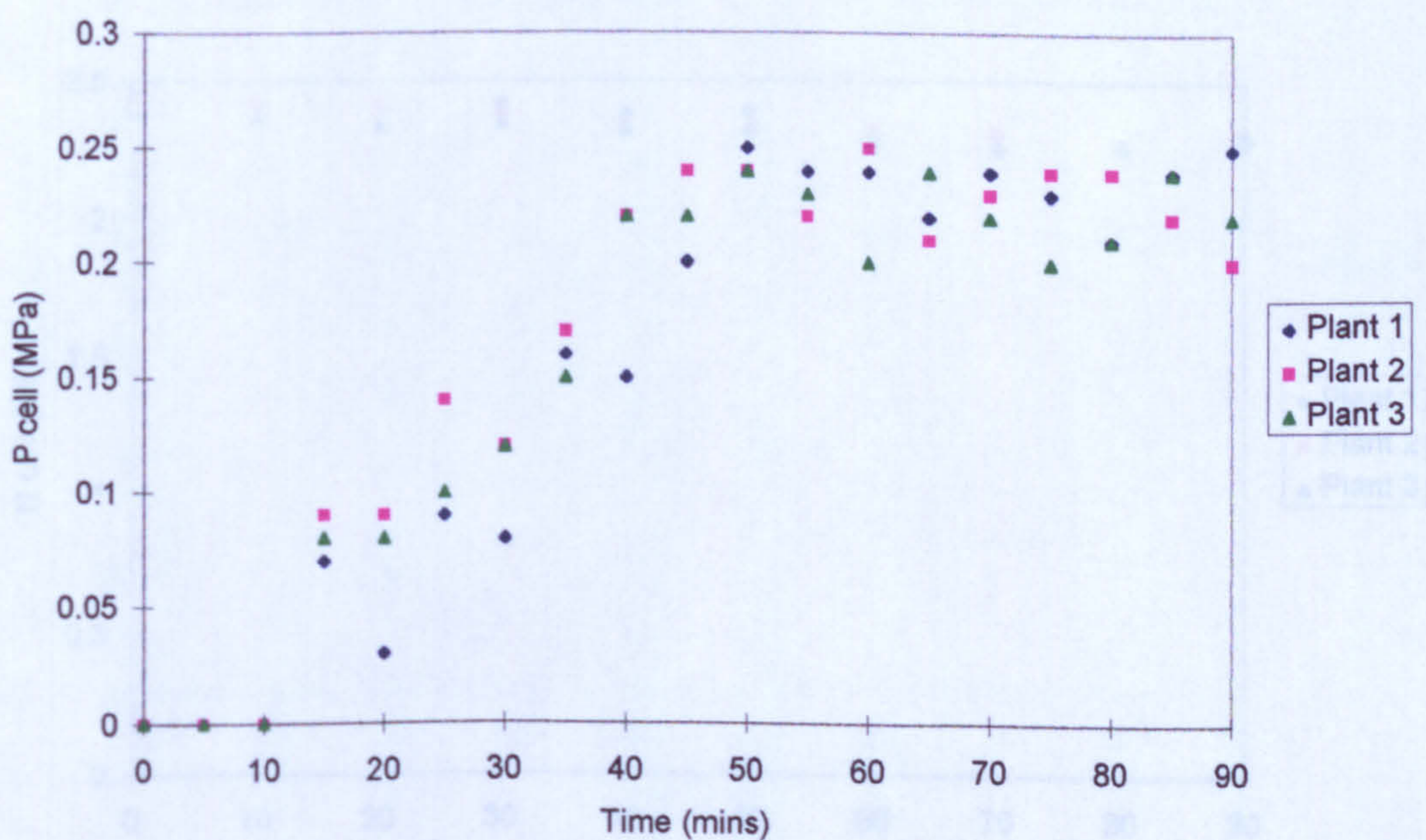
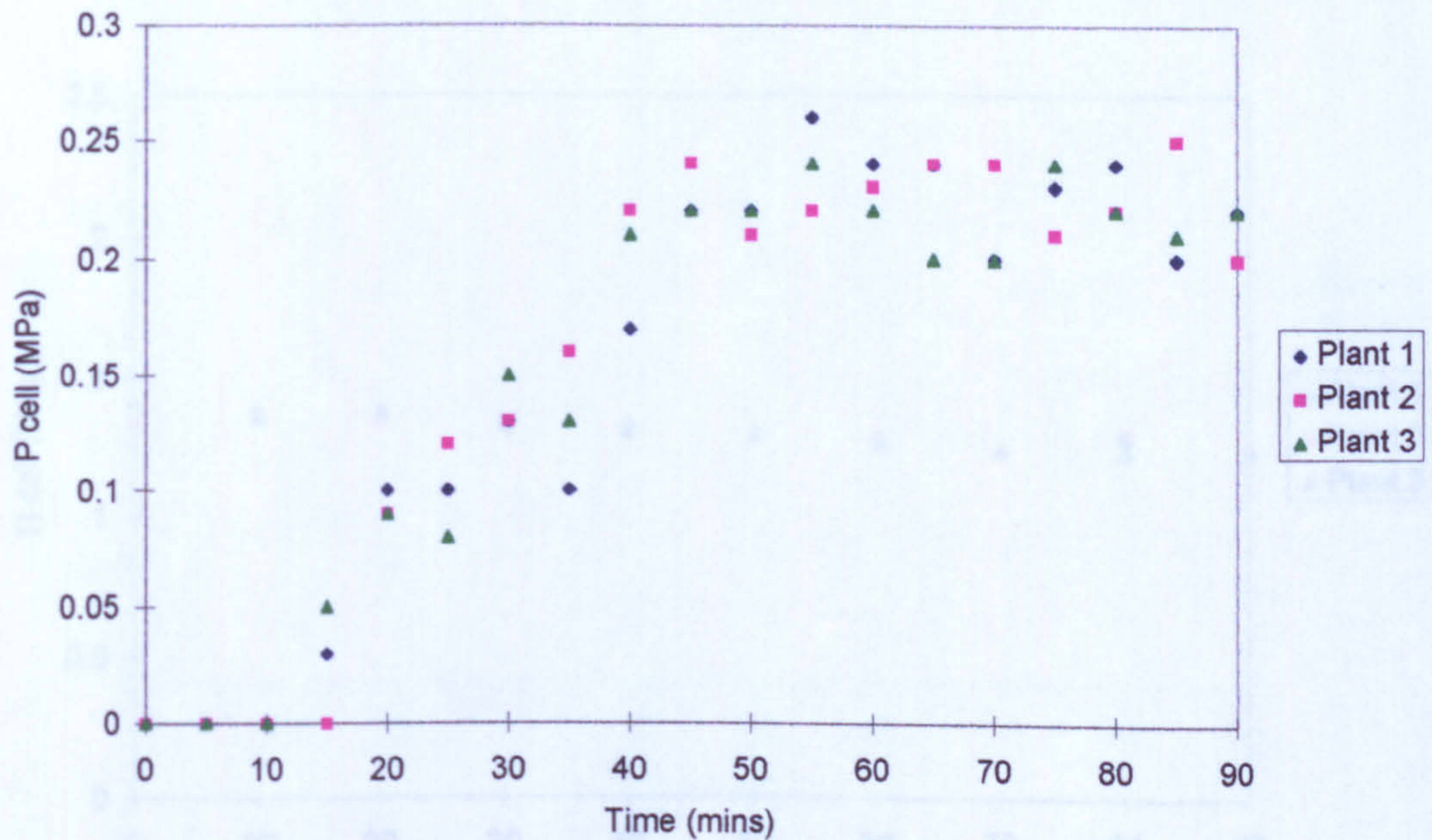
Returning to the closed system protocol, *Suaeda maritima* leaf slices were pre-treated in melibiose osmotica prior to being covered in water saturated silicone oil. Unlike NaCl, melibiose permeates the plasma membrane very slowly, and therefore, should not facilitate rapid turgor regulation. Leaf slices pre-treated in 500 mOsmoles  $\text{kg}^{-1}$  melibiose (0 mM NaCl plants, Figure 4.13) and 900 mOsmoles  $\text{kg}^{-1}$  melibiose (200 mM NaCl plants, Figure 4.14) had an initial leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) of 0.075 MPa to 0.1 MPa. This level of  $P_{\text{cell}}$  was maintained throughout the experiment; turgor pressure was not regulated upwards.

To ensure that the melibiose was not adversely affecting the leaf tissue, control osmotica were made up to a concentration which corresponded to the estimated concentration of solutes in the apoplast *in vivo*. Leaf slices pre-treated in 400 Osmoles  $\text{kg}^{-1}$  melibiose (0 mM NaCl plants, Figure 4.15) and 800 mOsmoles  $\text{kg}^{-1}$  melibiose (200 mM NaCl plants, Figure 4.16) maintained leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) at 0.2 MPa to 0.25 MPa, which is comparable to the leaf epidermal  $P_{\text{cell}}$  in intact plants (see Chapter 3, Figure 3.4), and also corresponds to the target  $P_{\text{cell}}$  level achieved by the turgor regulation mechanisms observed in freshly cut (see Figure 4.1 and 4.2) and NaCl pre-treated leaf slices (see Figure 4.5 and 4.6, and Figure 4.7 and 4.8).



**Figure 4.1 and Figure 4.2, Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in freshly sliced *Suaeda maritima* leaves under silicone oil (closed system)**

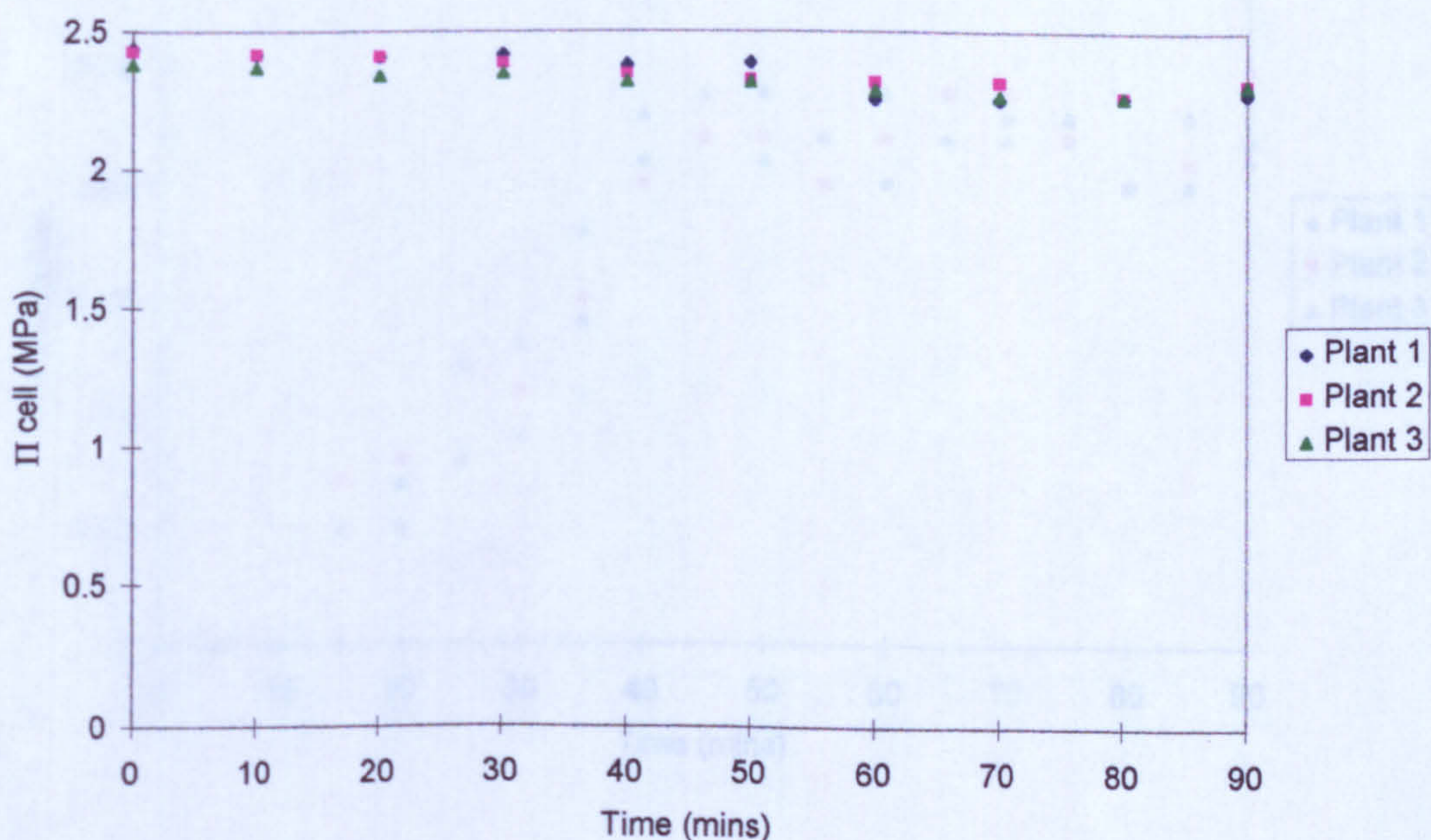
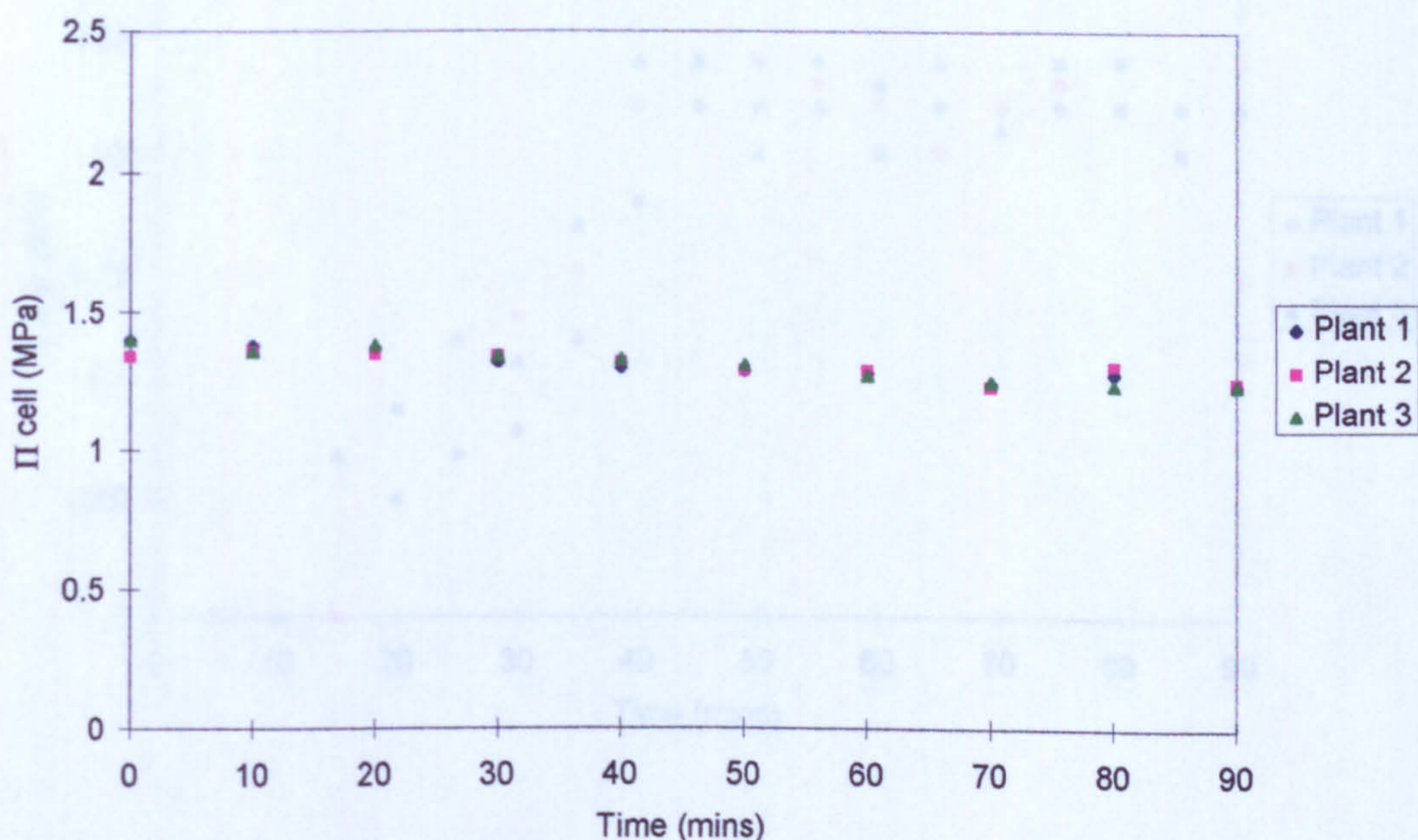
Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in freshly cut, longitudinal slices of *Suaeda maritima* leaves under silicone oil. The leaves were excised from plants grown in 0 mM (Figure 4.1, upper figure) and 200 mM NaCl (Figure 4.2, lower figure) at day 14; measurements were made on leaf pair 1 and 2 only. Turgor pressure was measured at 5 minute intervals for 90 minutes. Each datum point represents a single turgor pressure measurement at the time indicated.





**Figure 4.3 and Figure 4.4, Leaf epidermal osmotic pressure ( $\Pi_{\text{cell}}$ ) in freshly sliced *Suaeda maritima* leaves under silicone oil (closed system)**

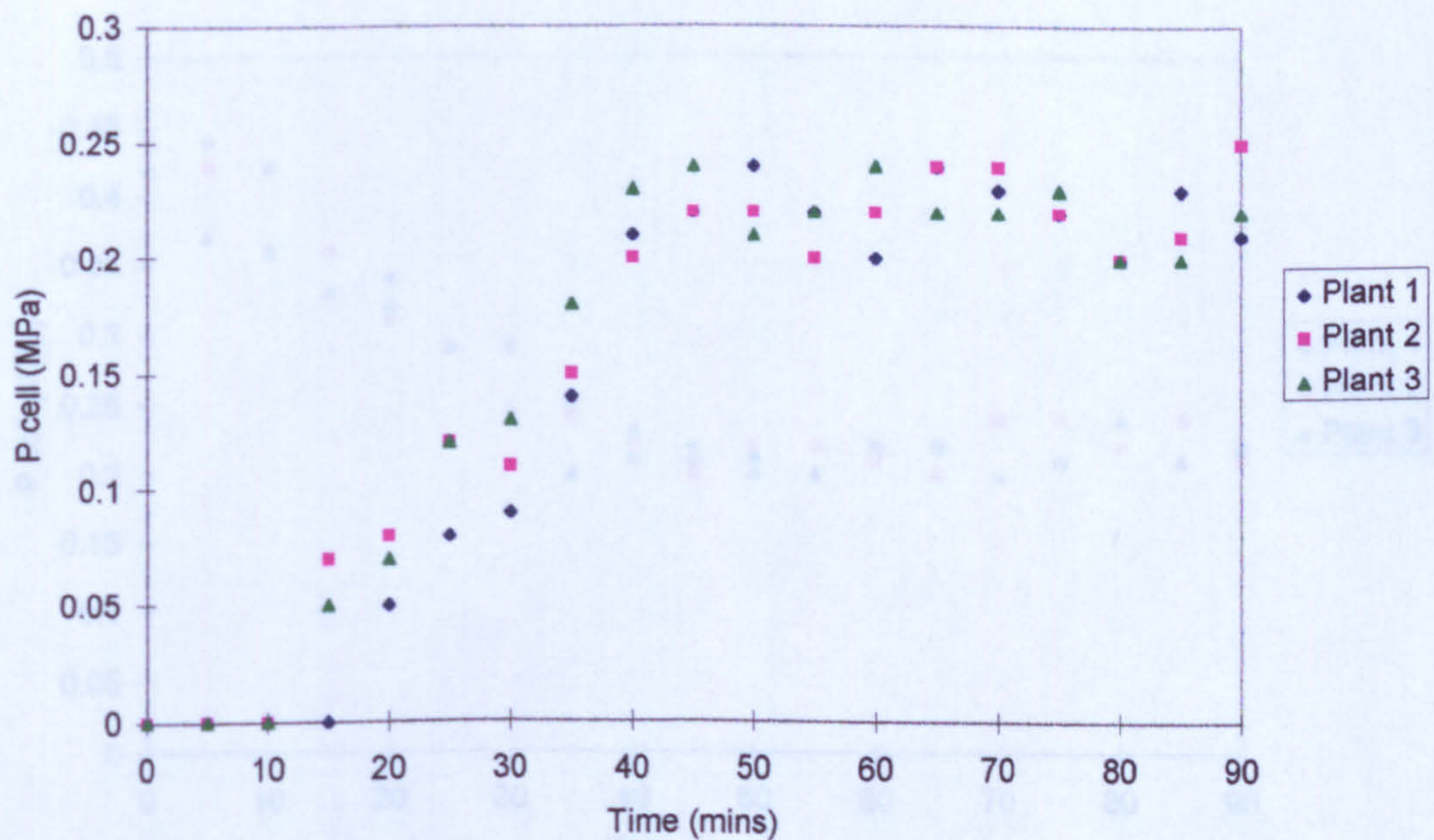
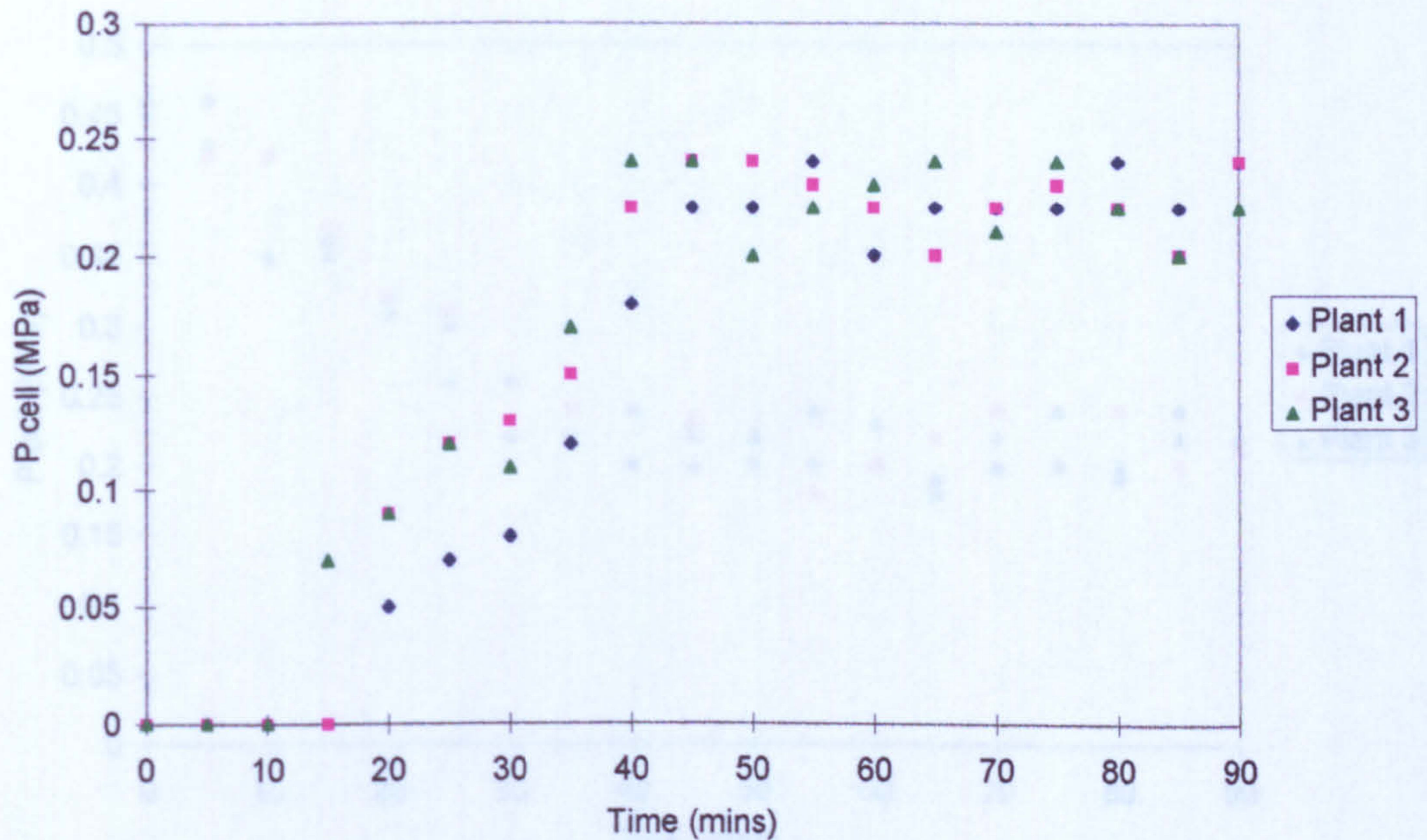
Leaf epidermal osmotic pressure ( $\Pi_{\text{cell}}$ ) in freshly cut, longitudinal slices of *Suaeda maritima* leaves under silicone oil. The leaves were excised from plants grown in 0 mM (Figure 4.3, upper figure) and 200 mM NaCl (Figure 4.4, lower figure) at day 14; measurements were made on leaf pair 1 and 2 only. Osmotic pressure was measured at 10 minute intervals for 90 minutes. Each datum point represents a single osmotic pressure measurement at the time indicated.





**Figure 4.5 and Figure 4.6, Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in *Suaeda maritima* leaf slices pre-treated in 600 - 1000 mOsmoles  $\text{kg}^{-1}$  NaCl (closed system)**

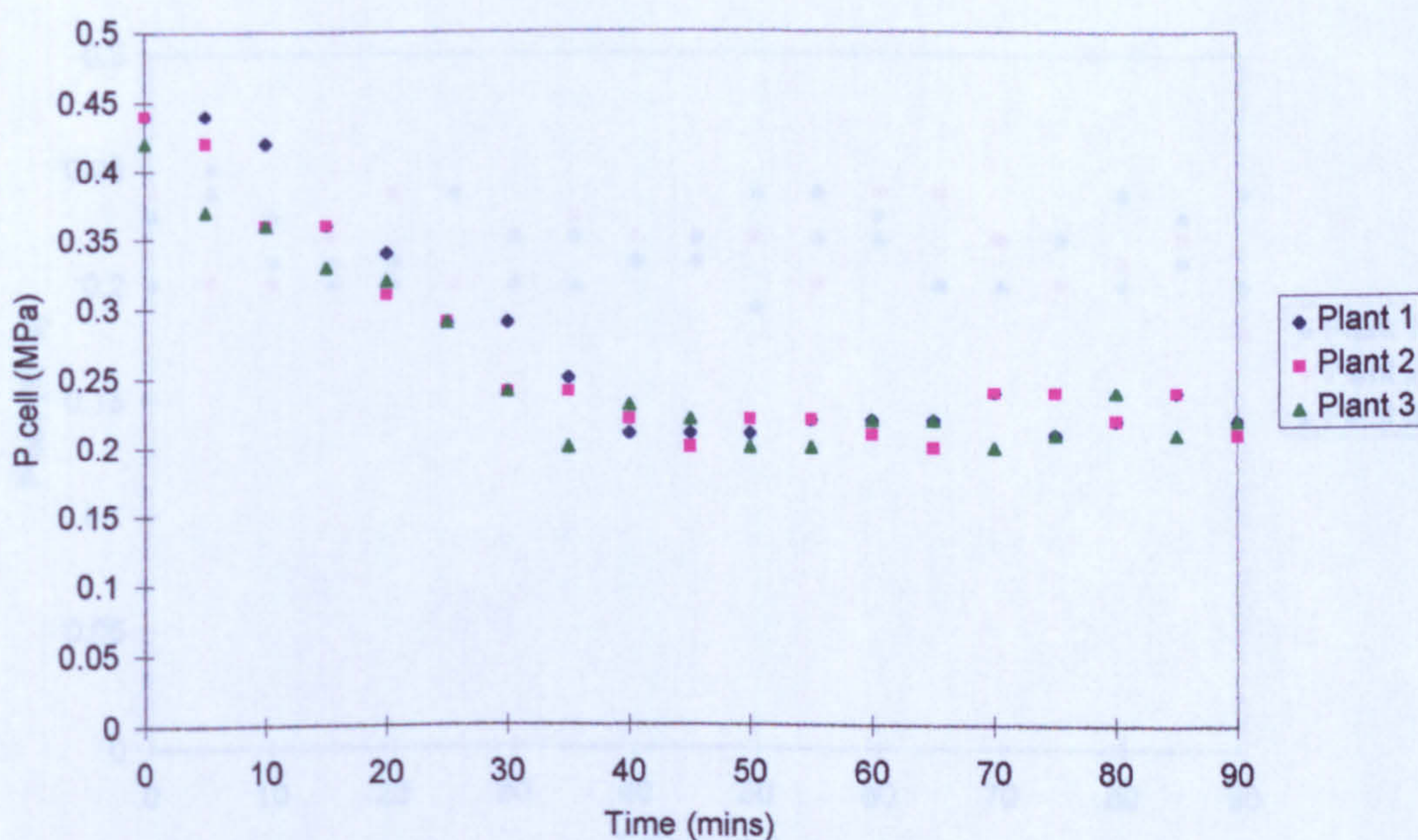
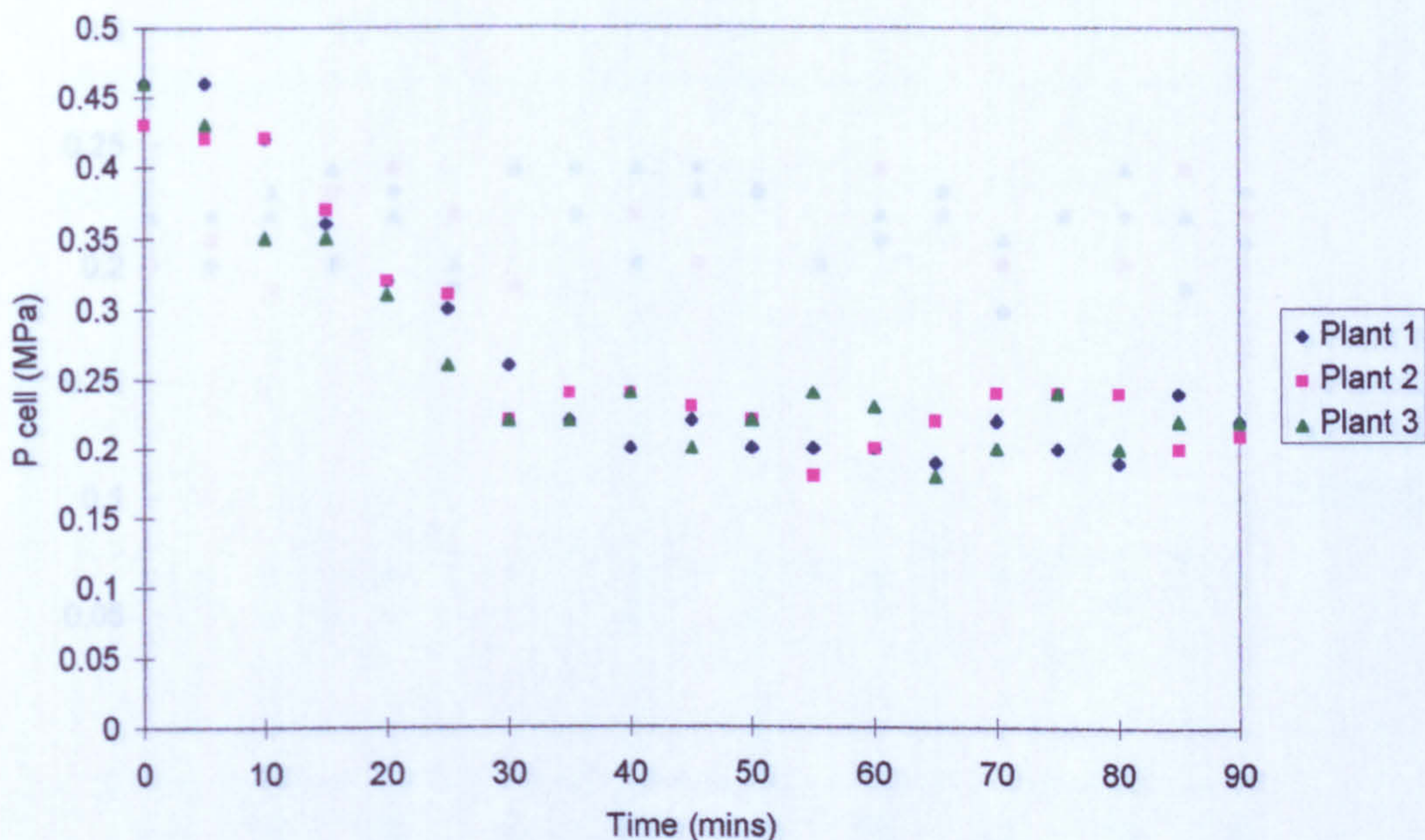
Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in pre-treated *Suaeda maritima* leaf slices under silicone oil. Leaves excised from plants grown in 0 mM and 200 mM NaCl were aerated in 600 mOsmoles  $\text{kg}^{-1}$  (Figure 4.5, upper figure) and 1000 mOsmoles  $\text{kg}^{-1}$  NaCl (Figure 4.6, lower figure) respectively for 15 minutes, prior to being covered in silicone oil. Turgor pressure measurements were taken at 5 minute intervals for 90 minutes.





**Figure 4.7 and Figure 4.8, Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in *Suaeda maritima* leaf slices pre-treated in 300 - 600 mOsmoles  $\text{kg}^{-1}$  NaCl (closed system)**

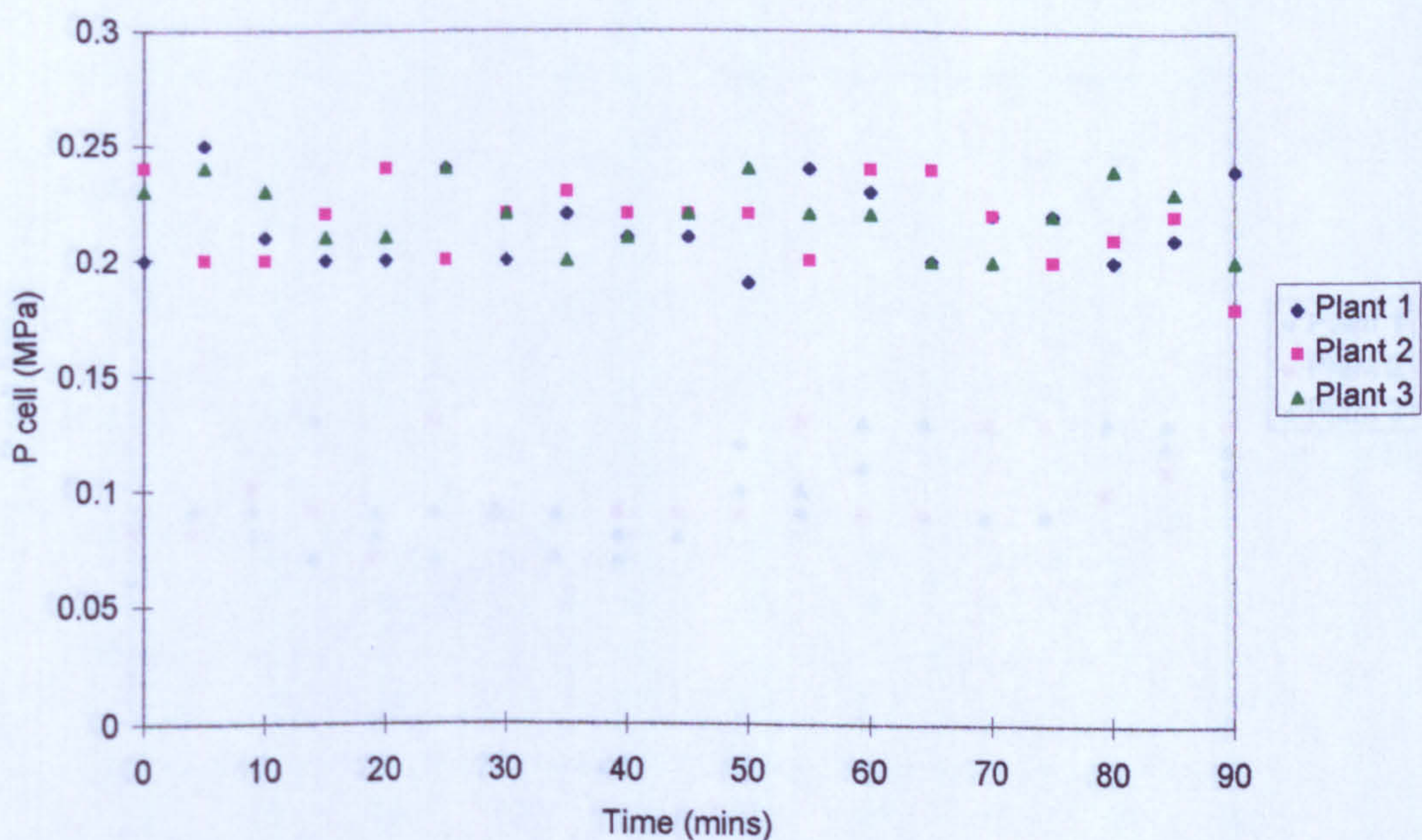
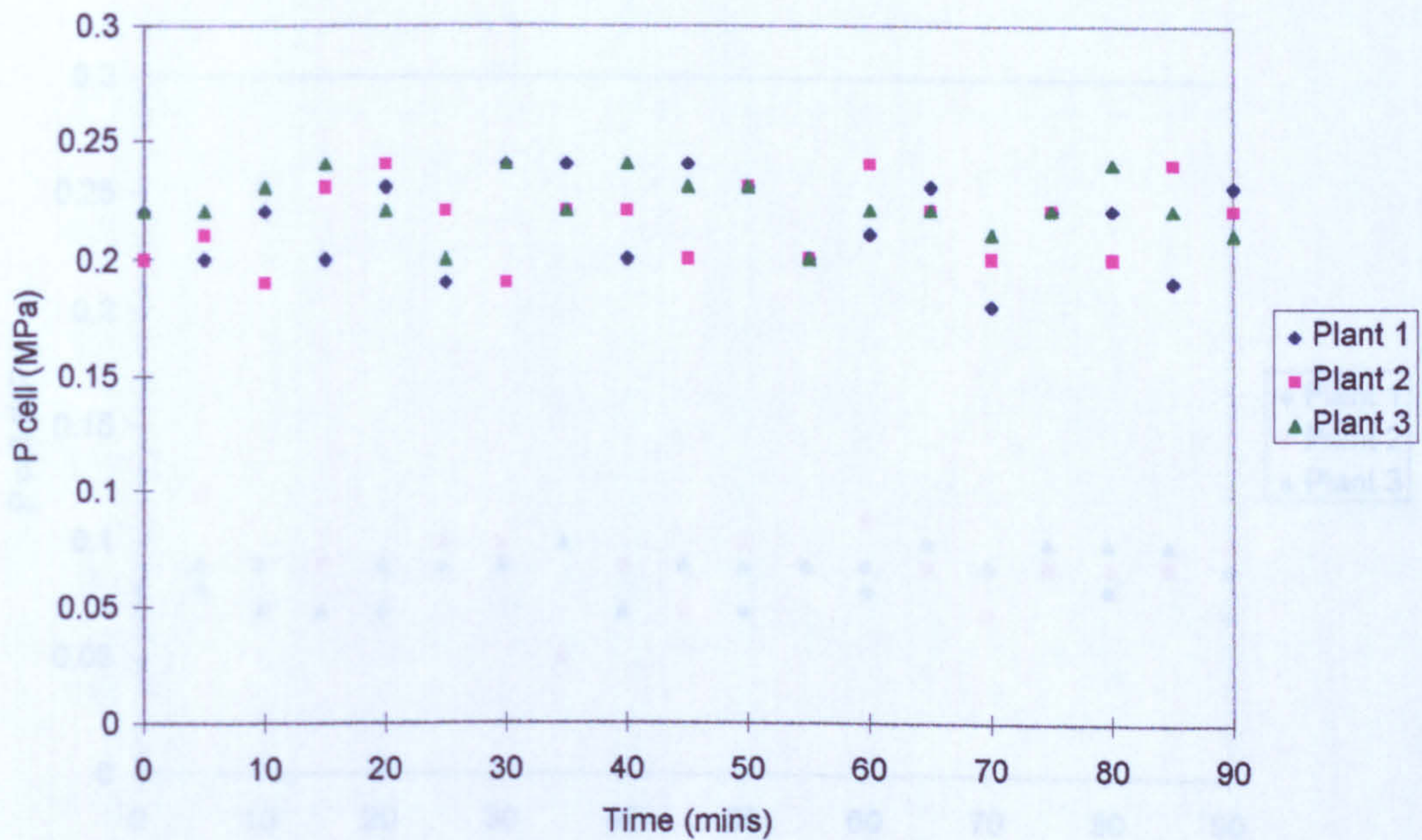
Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in pre-treated *Suaeda maritima* leaf slices under silicone oil. Leaves excised from plants grown in 0 mM and 200 mM NaCl were aerated in 300 mOsmoles  $\text{kg}^{-1}$  (Figure 4.7, upper figure) and 600 mOsmoles  $\text{kg}^{-1}$  NaCl (Figure 4.8, lower figure) respectively for 15 minutes, prior to being covered in silicone oil. Turgor pressure measurements were taken every 5 minutes for a maximum of 90 minutes.





**Figure 4.9 and Figure 4.10, Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in *Suaeda maritima* leaf slices pre-treated in 400 - 800 mOsmoles  $\text{kg}^{-1}$  NaCl (closed system)**

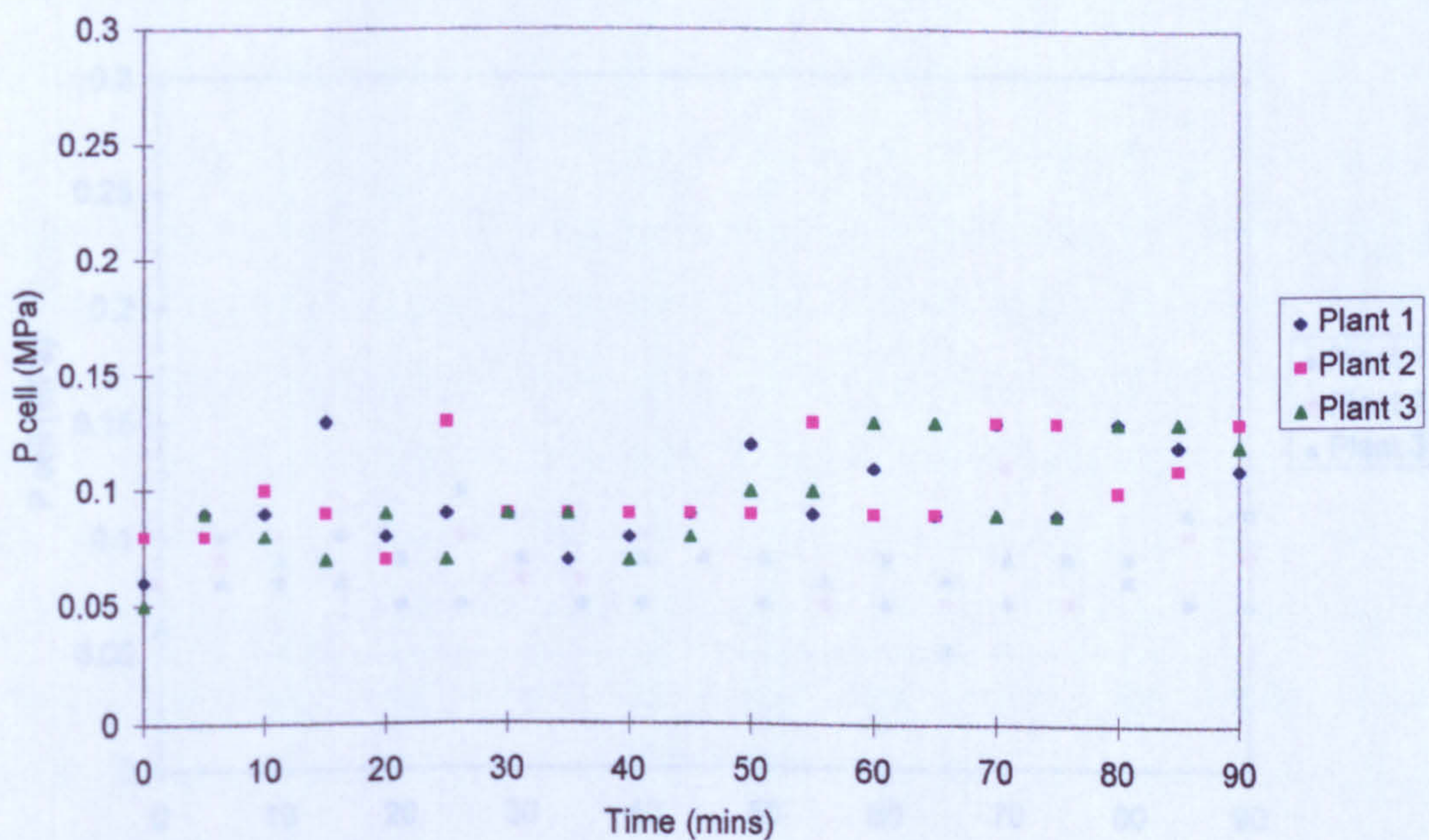
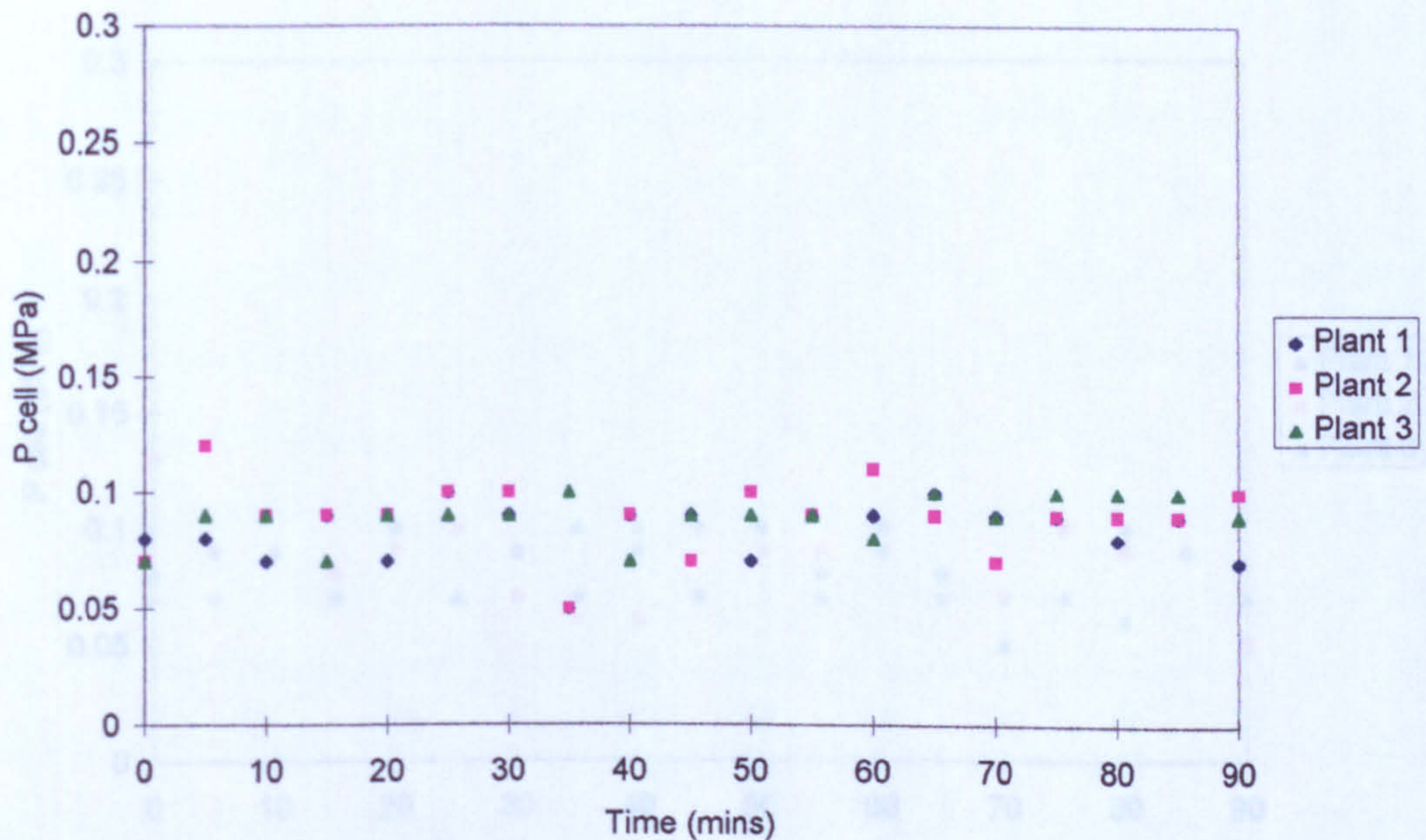
Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in pre-treated *Suaeda maritima* leaf slices under silicone oil. Leaves excised from plants grown in 0 mM and 200 mM NaCl were aerated in 400 mOsmoles  $\text{kg}^{-1}$  (Figure 4.9, upper figure) and 800 mOsmoles  $\text{kg}^{-1}$  NaCl (Figure 4.10, lower figure) respectively for 15 minutes, prior to being covered in silicone oil. Turgor pressure measurements were taken every 5 minutes for 90 minutes.





**Figure 4.11 and Figure 4.12, Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in *Suaeda maritima* leaf slices bathed in 500 - 900 mOsmoles  $\text{kg}^{-1}$  NaCl (open system)**

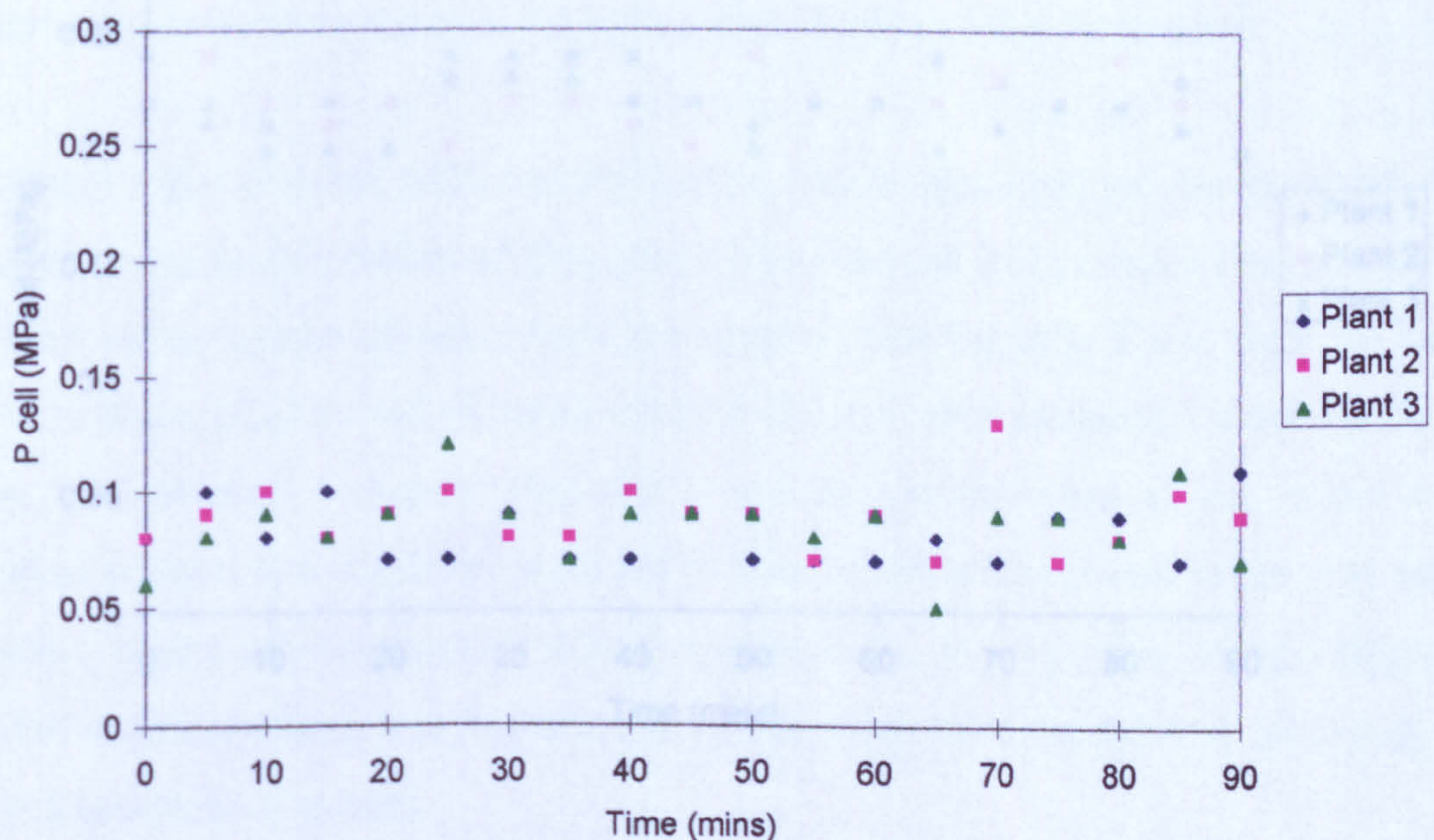
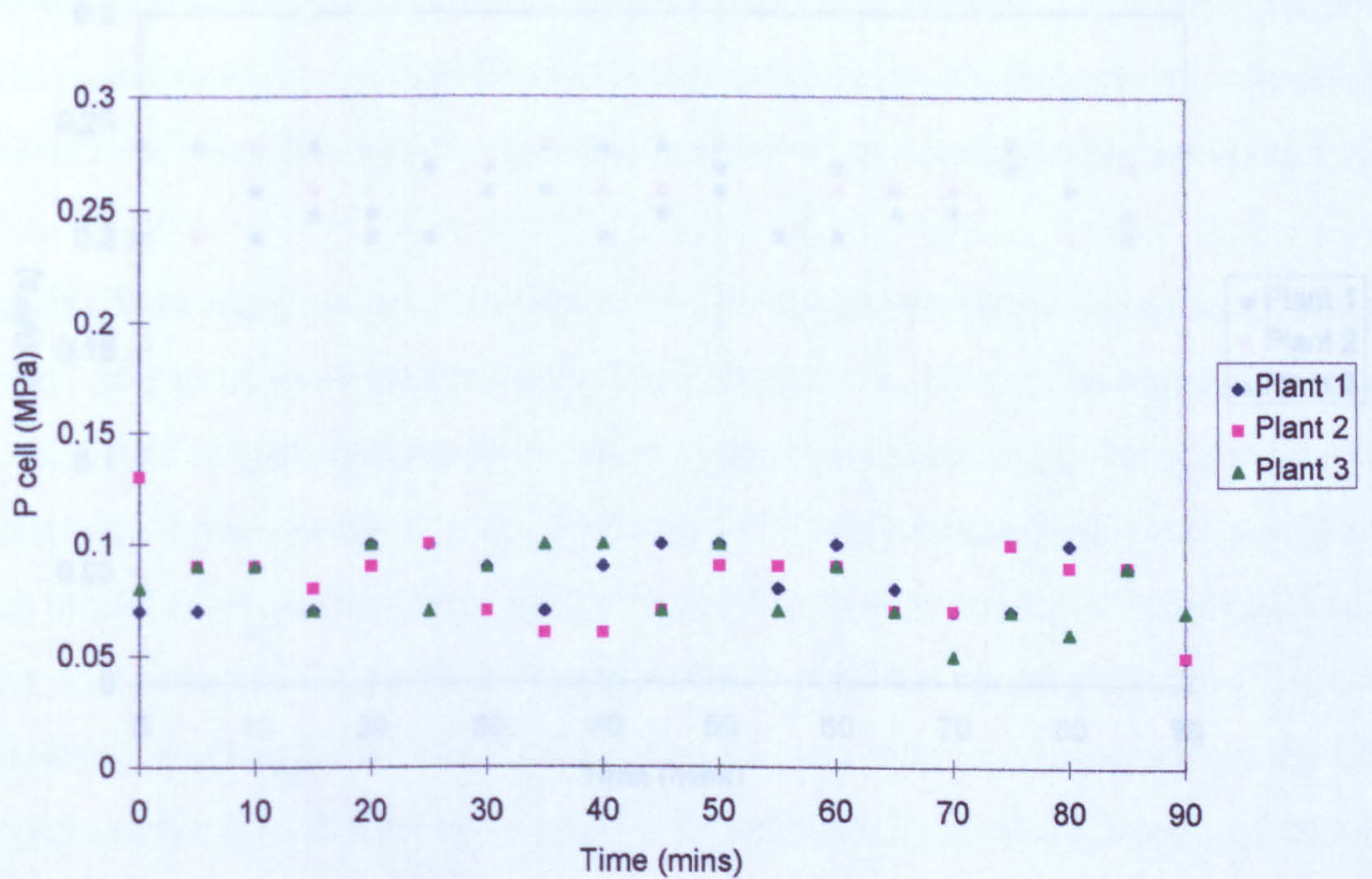
Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in *Suaeda maritima* leaf slices bathed in aqueous NaCl osmotica. Leaves excised from plants grown in 0 mM and 200 mM NaCl were bathed in 500 mOsmoles  $\text{kg}^{-1}$  (Figure 4.11, upper figure) and 900 mOsmoles  $\text{kg}^{-1}$  NaCl (Figure 4.12, lower figure) respectively. Turgor pressure measurements commenced after 15 minutes in the osmotica;  $P_{\text{cell}}$  was measured every 5 minutes for 90 minutes thereafter.





**Figure 4.13 and Figure 4.14, Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in *Suaeda maritima* leaf slices pre-treated in 500 - 900 mOsmoles  $\text{kg}^{-1}$  melibiose (closed system)**

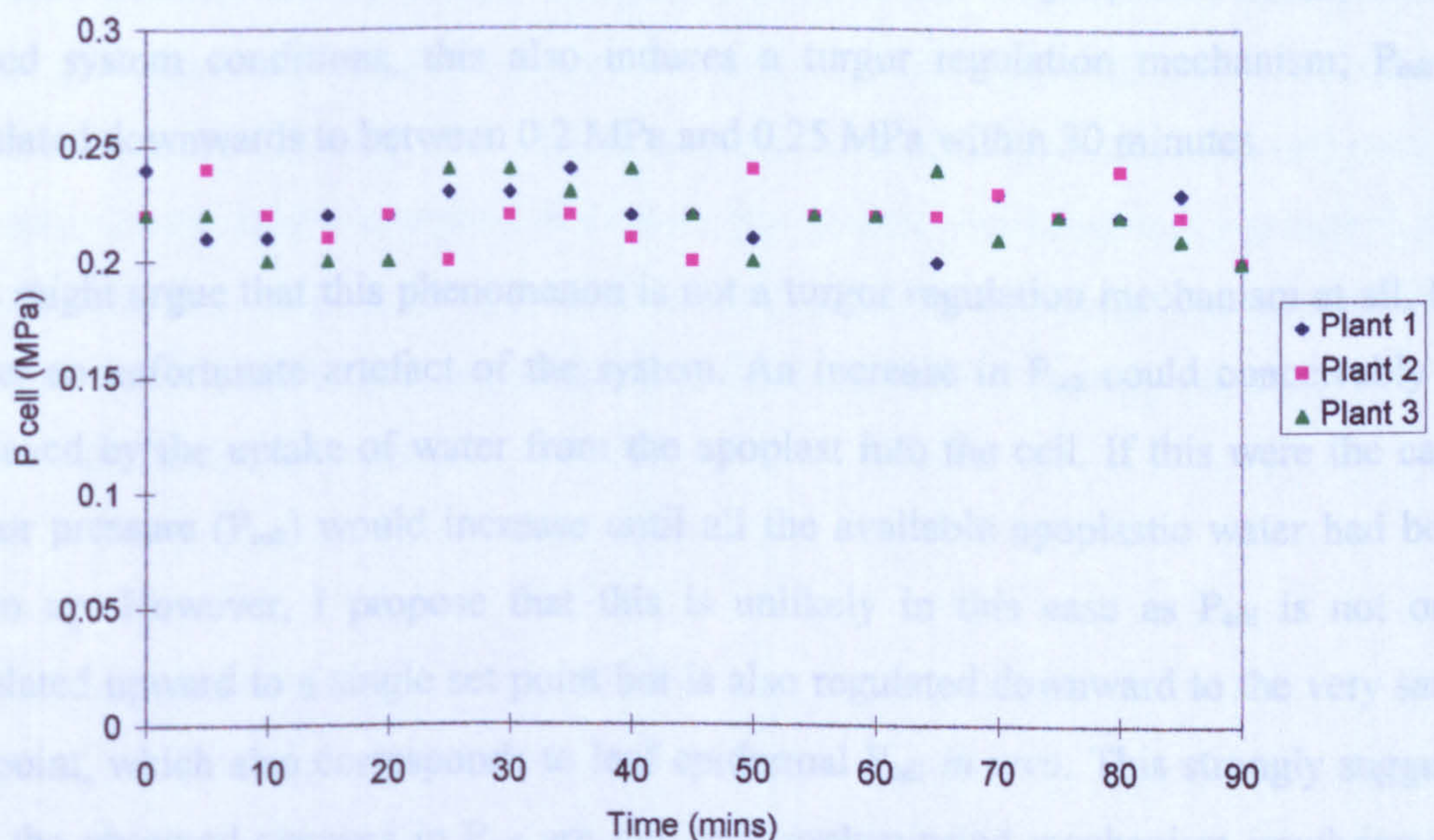
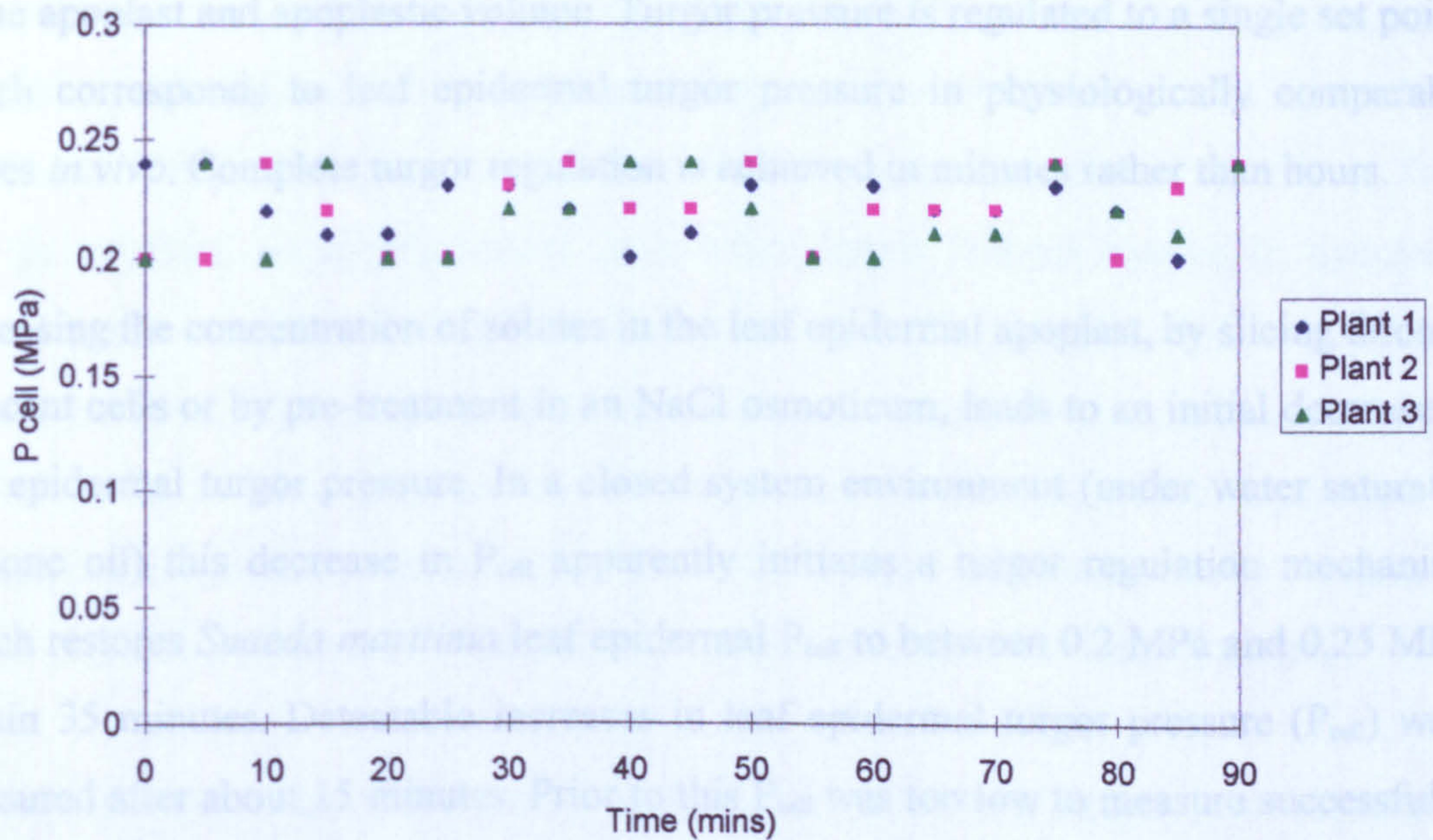
Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in pre-treated *Suaeda maritima* leaf slices under silicone oil. Leaves excised from plants grown in 0 mM and 200 mM NaCl were aerated in 500 mOsmoles  $\text{kg}^{-1}$  (Figure 4.13, upper figure) and 900 mOsmoles  $\text{kg}^{-1}$  melibiose (Figure 4.14, lower figure) respectively for 15 minutes, prior to being covered in silicone oil. Turgor pressure measurements were taken every 5 minutes for 90 minutes.





**Figure 4.15 and Figure 4.16, Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in *Suaeda maritima* leaf slices pre-treated in 400 - 800 mOsmoles  $\text{kg}^{-1}$  melibiose (closed system)**

Leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) in pre-treated *Suaeda maritima* leaf slices under silicone oil. Leaves excised from plants grown in 0 mM and 200 mM NaCl were aerated in 400 mOsmoles  $\text{kg}^{-1}$  (Figure 4.15, upper figure) and 800 mOsmoles  $\text{kg}^{-1}$  melibiose (Figure 4.16, lower figure) respectively for 15 minutes, prior to being covered in silicone oil. Turgor pressure measurements were taken every 5 minutes for 90 minutes.





## 4.4, Discussion

The data presented in this chapter demonstrates that *Suaeda maritima* leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) can be modulated by manipulating the solutes present in the adjacent apoplastic compartment. These changes in turgor pressure induce an osmotic adjustment mechanism leading to turgor regulation. The osmotic adjustment of solutes is apoplastic in nature, and strongly dependent on the permeability of the solutes present in the apoplast and apoplastic volume. Turgor pressure is regulated to a single set point, which corresponds to leaf epidermal turgor pressure in physiologically comparable leaves *in vivo*. Complete turgor regulation is achieved in minutes rather than hours.

Increasing the concentration of solutes in the leaf epidermal apoplast, by slicing through adjacent cells or by pre-treatment in an NaCl osmoticum, leads to an initial decrease in leaf epidermal turgor pressure. In a closed system environment (under water saturated silicone oil) this decrease in  $P_{\text{cell}}$  apparently initiates a turgor regulation mechanism which restores *Suaeda maritima* leaf epidermal  $P_{\text{cell}}$  to between 0.2 MPa and 0.25 MPa, within 35 minutes. Detectable increases in leaf epidermal turgor pressure ( $P_{\text{cell}}$ ) were measured after about 15 minutes. Prior to this  $P_{\text{cell}}$  was too low to measure successfully. Decreasing the concentration of solutes in the apoplast, by aerating sliced leaf tissue in a dilute NaCl osmoticum, leads to an initial increase in cell turgor pressure ( $P_{\text{cell}}$ ). Under closed system conditions, this also induces a turgor regulation mechanism;  $P_{\text{cell}}$  is regulated downwards to between 0.2 MPa and 0.25 MPa within 30 minutes.

One might argue that this phenomenon is not a turgor regulation mechanism at all, but rather an unfortunate artefact of the system. An increase in  $P_{\text{cell}}$  could conceivably be achieved by the uptake of water from the apoplast into the cell. If this were the case, turgor pressure ( $P_{\text{cell}}$ ) would increase until all the available apoplastic water had been taken up. However, I propose that this is unlikely in this case as  $P_{\text{cell}}$  is not only regulated upward to a single set point but is also regulated downward to the very same set point, which also corresponds to leaf epidermal  $P_{\text{cell}}$  *in vivo*. This strongly suggests that the observed changes in  $P_{\text{cell}}$  are due to a sophisticated mechanism involving the active adjustment of solutes.



The short time scale in which turgor regulation is achieved in *Suaeda maritima* leaf epidermal cells in this case, suggests that the observed regulation mechanism is not due to osmotic adjustment of solutes in the protoplast; classical osmotic adjustment of the protoplast in marine algae and higher plants can often take up to 24 hours (Cram, 1976; see also Chapter 3). To test this hypothesis leaf epidermal cell osmotic pressure ( $\Pi_{\text{cell}}$ ) measurements were taken during turgor regulation. The data obtained demonstrated that the concentration of solutes in the protoplast remained unchanged throughout. This leads to the conclusion that osmotic adjustment of solutes, resulting in turgor regulation, takes place in the apoplast rather than the protoplast in this case. Cram (1976 and 1980) pointed out that the flux of solutes across the plasma membrane, from cell to apoplast, invariably results in a much larger relative change in apoplastic osmotic pressure ( $\Pi_{\text{wall}}$ ) than in that of the protoplast ( $\Pi_{\text{cell}}$ ). This is due to very much smaller relative volume of the wall. Since turgor pressure ( $P_{\text{cell}}$ ) is governed by the difference in osmotic pressure across the plasma membrane, active adjustment of solutes in the apoplast could provide a plant with a rapid and metabolically inexpensive turgor regulation mechanism that does not require protoplastic solute adjustment.

Tomos and Wyn Jones (1988) published data which pointed to an apoplastic adjustment mechanism in red beet taproot tissue. Freshly cut red beet taproot discs bathed in water saturated silicone oil had an initial turgor pressure of just below 0.2 MPa. Increases in turgor pressure were observed almost immediately, reaching a plateau after about 2 hours at between 0.2 - 0.3 MPa. There was no corresponding increase in cell osmotic pressure. These data correspond well with the *Suaeda maritima* leaf epidermal data presented in this chapter. Similar experiments carried out on sugar beet taproot discs provide data which further supports these findings. These data are discussed in the following chapter (Chapter 5).



## 4.5, Summary and conclusions

- ❑ Modulating the solute concentration in the apoplast of *Suaeda maritima* leaf epidermal cells, by slicing the leaf open longitudinally or by pre-treating leaf slices in an osmoticum, leads to changes in leaf epidermal cell turgor pressure ( $P_{\text{cell}}$ ).
- ❑ Changes in  $P_{\text{cell}}$  initiate a turgor regulation mechanism which is strongly dependent on apoplastic volume and solute permeability.
- ❑ Providing the apoplast is closed to the external environment by a protective layer of water saturated silicone oil (a closed system which attempts to achieve a similar apoplastic environment and volume to that found *in vivo*), upward and downward turgor regulation is achieved within 30 - 40 minutes.
- ❑ Turgor pressure is regulated to a single set point (around 0.2 MPa) which corresponds to leaf epidermal  $P_{\text{cell}}$  in comparable intact leaves that have not been excised from the plant.
- ❑ Upward and downward turgor regulation is not accompanied by an equivalent change in cell osmotic pressure ( $\Pi_{\text{cell}}$ ). This leads to the conclusion that osmotic adjustment leading to turgor regulation is apoplastic in nature rather than protoplasmic. This provides clear evidence that apoplastic solutes are readily utilised by *Suaeda maritima* leaf epidermal cells to maintain leaf epidermal  $P_{\text{cell}}$  at a level predetermined by the plant. By utilising the apoplastic space as an osmotic compartment *Suaeda maritima* can achieve turgor regulation quickly, while minimising metabolic expenditure.
- ❑ The observed turgor regulation mechanism is an excellent example of a turgor-dependent mechanism, in which a change in  $P_{\text{cell}}$  is detected and countered by modulation of membrane transport mechanisms. The nature of the



turgor-sensing mechanism, and subsequent signal transduction pathway, which leads to membrane transport remains unclear.



## Chapter 5: Turgor regulation in an open and a closed system in *Beta vulgaris* L. (sugar beet) taproot tissue

### 5.1, Introduction

Sugar beet (*Beta vulgaris* L.) belongs to the same family as *Suaeda maritima* - the family *Chenopodiaceae*. In common with *Suaeda maritima* leaf epidermal cells (see Chapter 3), sugar beet taproot parenchyma cells accumulate a high concentration of solutes in the protoplast (namely sucrose in this case), while maintaining a constant turgor pressure (Tomos *et al.*, 1992). The osmotic pressure ( $\Pi_{\text{cell}}$ ) of a sugar beet taproot increases from 0.7 MPa to 2.0 MPa as sucrose accumulates in the parenchyma cells during maturation. Turgor pressure ( $P_{\text{cell}}$ ), however, is maintained between 0.6 MPa and 0.7 MPa throughout the growing season (Tomos *et al.*, 1992).

As I pointed out in Chapter 3, assuming a reflection coefficient of 1, the turgor pressure of a cell is determined by the osmotic pressure of the cell ( $\Pi_{\text{cell}}$ ), the osmotic pressure of the adjacent apoplast/cell wall ( $\Pi_{\text{wall}}$ ) and by the hydrostatic component of the apoplast - the transpiration tension ( $P_{\text{wall}}$ ). Therefore the difference between  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  in sugar beet taproot parenchyma cells can only be attributed to properties of the apoplast. Tomos *et al.* (1992) measured turgor pressure in intact, mature taproots under transpiring (during the day) and non-transpiring (at night when the stomata are assumed to be largely closed and transpiration minimal) conditions. These data revealed that turgor pressure in non transpiring beet plants was approximately 0.1 MPa greater than in equivalent transpiring plants. This increase of 0.1 MPa accounts for only 7 % of the difference between  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$ . Therefore, it is reasonable to conclude that *Beta vulgaris* storage parenchyma cells utilise apoplastic solutes to maintain  $P_{\text{cell}}$ . I propose that this turgor maintenance mechanism is directly comparable to that found in *Suaeda maritima* leaf epidermal cells (Chapter 3 and 4).

This chapter describes experiments carried out on excised sugar beet taproot tissue. The cell pressure probe and picolitre osmometry (see Chapter 2, Section 2.2 and 2.5) were used to measure turgor regulation and osmotic adjustment in beet discs in an aqueous open system and a closed system (see also Chapter 4).



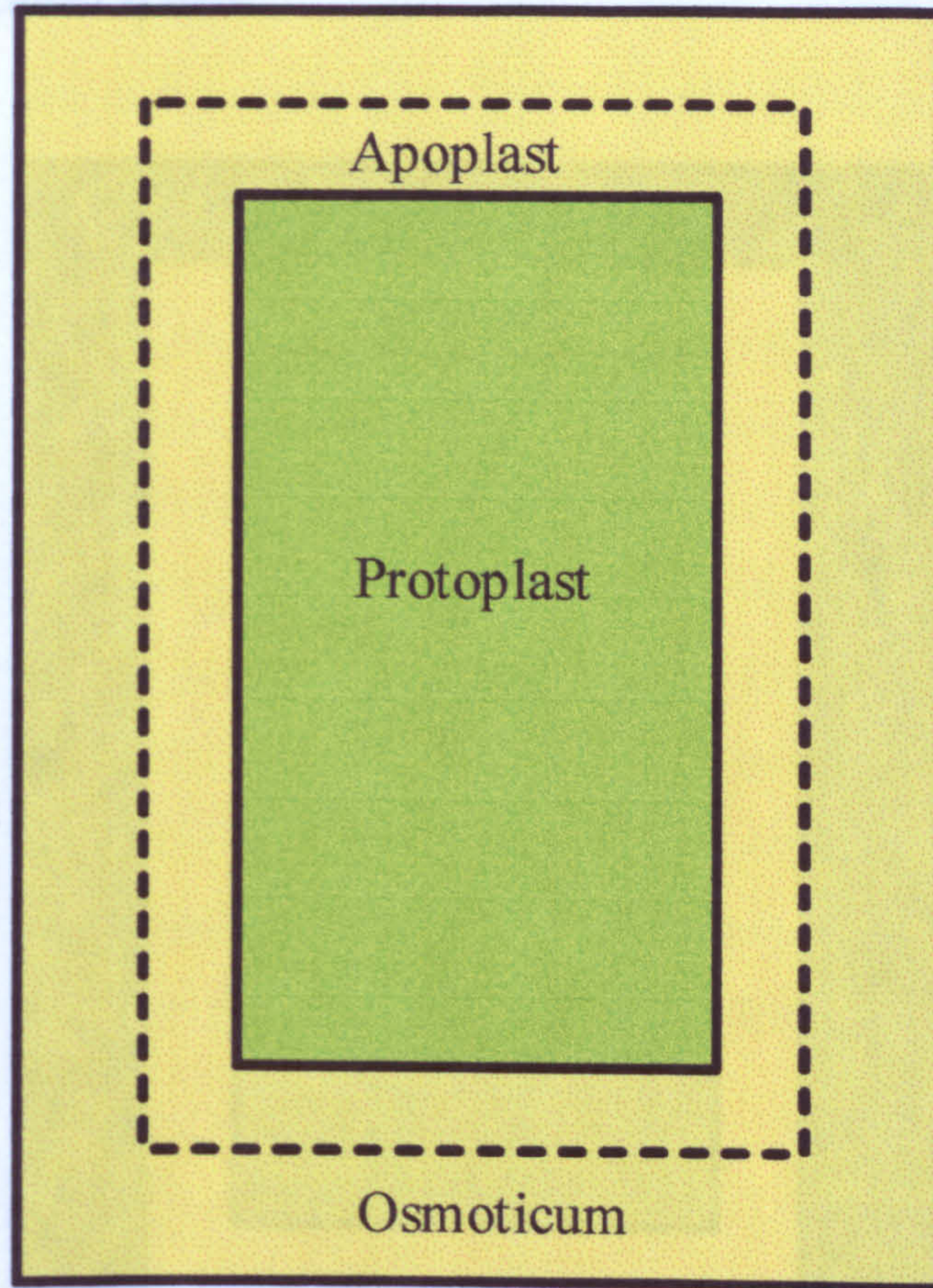
In the open system, beet discs are vigorously aerated in a range of mannitol osmotica over a number of days. This treatment is often referred to as ageing and is known to have a profound effect on the physiology and biochemistry of storage tissue; most notably an increase in protein synthesis and respiration, followed by an increase in solute uptake (for reviews see Van Steveninck, 1975; Poole, 1976). The apoplast of beet tissue in an open system is presumably completely open to the well stirred external medium (hence the term **open system** - see **Figure 5.1**), and therefore effectively occupies the same volume as the bathing osmoticum. Osmotic adjustment leading to turgor regulation is likely to be confined to the protoplast due to the artificially large volume of the apoplast.

The closed system (introduced in **Chapter 4**) attempts to mimic the apoplastic environment *in vivo* (Tomos and Wyn Jones, 1988). Sugar beet taproot discs (freshly cut or pre-treated in an osmoticum) are covered in water saturated silicone oil, which closes the apoplast and prevents tissue dehydration (hence the term **closed system** - see **Figure 5.2**). Under these conditions the apoplast occupies only a small percentage of the total tissue volume, which is comparable to the situation in the intact taproot (see Pitman, 1963; Leigh and Tomos 1983). Given the small volume of apoplast relative to protoplast, and assuming that silicone oil acts only as an inert barrier that cannot take part in the exchange of solutes or water (in either direction), the cell should be able to control and modulate the solutes in the apoplastic compartment by means of membrane transport. The closed system ensures that the protoplast and apoplast are available for osmotic adjustment purposes, and thus provides an excellent model system from which to study turgor regulation.



**Figure 5.1, The open system**

*Figure 5.2, The closed system*

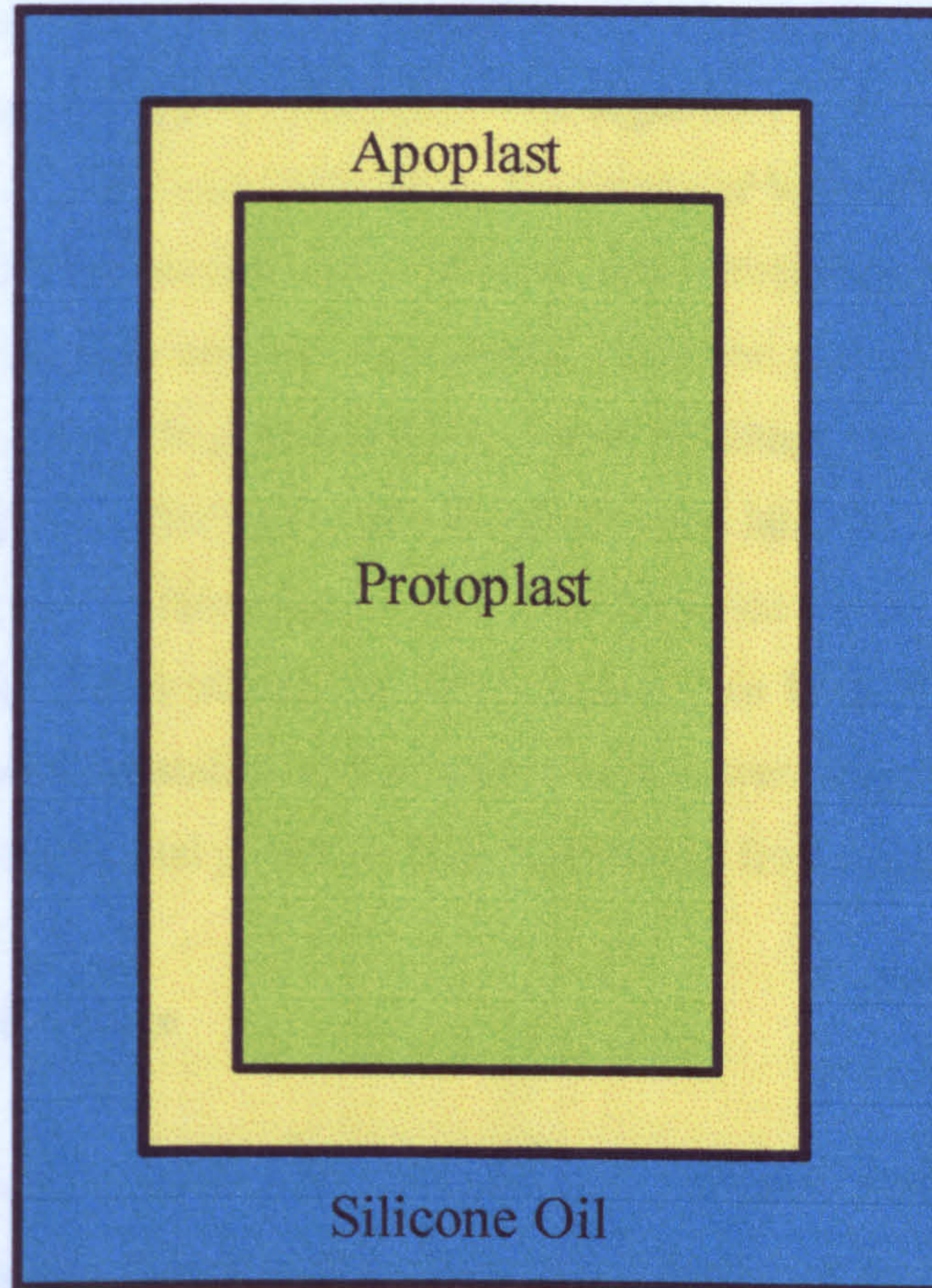




## 5.2. Methods

### 5.2.1. Construction of a closed system

**Figure 5.2, The closed system**





## **5.2, Method**

### **5.2.1, Germination and growth conditions**

Sugar beet seeds (Gala variety) were a kind gift from Michael Coy at the English Sugar Beet Company Ltd, Lincolnshire. The seeds were in pellet form (monogerm), coated with a fungicide and insecticide treatment. The sugar beet were germinated out in the open, on the roof of the Memorial Building, University of Wales Bangor, in March. Six seeds were placed in 4 cm deep wells in small pots containing John Innes Number 1 compost. The seeds were covered with compost and the pots were watered to field capacity daily. As the seeds germinated the weaker seedlings were removed until only one seedling remained. After two weeks the plants were large enough to be transferred into larger 8 litre pots. At this stage the beet were fed twice a week using a commercial fertiliser (Phostrogen) and watered to field capacity (see Plate 5.1) every other day. Treatments for aphid infestation and powdery mildew were applied as required using widely available commercial products (Zeneca) obtained from a local garden centre.

### **5.2.2, Harvest and storage**

The sugar beet were harvested after 6 months (September/October). All leaves were carefully cut away and discarded. The taproots were washed in cold water and dried thoroughly with tissue paper. After drying, the taproots were placed in plastic sacks (ten taproots per sack) between layers of dry, protective compost, and stored at 5 °C in a cold room. The sugar beet taproots were used within 8 weeks of harvest; after 8 weeks all remaining beet were discarded. During a sugar beet shortage (due to a poor harvest and cold room malfunction) Dr David Wright, School of Agriculture and Forest Sciences at the University of Wales Bangor, very kindly arranged delivery of freshly harvested beet taproots (Zulu variety) from a British Sugar beet farm in Shropshire. These taproots were cleaned and stored as described above.



### 5.2.3, Beet disc preparation

Suitable sugar beet taproots (intact and healthy) were selected from storage, washed and dried. The taproots were cut into three thick transverse slices using a sharp kitchen knife. The upper slice or crown was discarded. A sharp 7 mm diameter cork borer was used to cut cores of storage parenchyma tissue from the lower root slices. Each core of tissue was immediately placed in 300 mM mannitol/0.5 mM CaSO<sub>4</sub> (BDH) solution in order to prevent dehydration and loss of cell solutes. Once an adequate number of cores had been obtained a sharp double edged razor blade was used to cut 1 mm thick discs. The discs were rinsed in 300 mM mannitol/0.5 mM CaSO<sub>4</sub> before being drained and transferred to the experimental osmotica in 5 litre round bottomed flasks. Approximately 200 discs were placed in each flask. All sugar beet discs were freshly cut and used immediately (after Wyse *et al.*, 1986; Perry *et al.*, 1987).

### 5.2.4, The open system

Sugar beet taproot discs were aged for 7 days in 5 litre round bottomed flasks containing 0 - 600 mOsmoles kg<sup>-1</sup> mannitol and 0.5 mM CaSO<sub>4</sub>. Each flask was aerated via tubing connected to a compressed air supply. Care was taken to ensure that the beet discs circulated freely and did not settle at the bottom of the flasks. The bathing osmotica were changed every 12 hours to minimise the growth of bacteria.

Discs were sampled at the times indicated. Individual discs were secured to a perspex sample holder and covered in a small volume of osmoticum (5 - 10 ml). Turgor pressure ( $P_{\text{cell}}$ ) was measured using the cell pressure probe (see Chapter 2, Section 2.2) and osmotic pressure ( $\Pi_{\text{cell}}$ ) was measured using the picolitre osmometer (Chapter 2, Section 2.5). At least 5 discs were sampled from each flask, three measurements were made on each disc. The cells targeted were the large storage parenchyma cells at the periphery of the discs (after Perry *et al.*, 1987).



### 5.2.5, The closed System

A single core of sugar beet taproot tissue (storage parenchyma) was cut using a sharp 7 mm diameter cork borer. The core of beet tissue was sliced into 1 mm thick discs using a sharp double edged razor blade. The discs were either used immediately or after pre-treatment in an osmoticum. Pre-treatment involved aerating 10 beet discs in 100 ml of osmoticum for 15 minutes. The osmotica used were: deionised water, 300 - 600 mOsmoles  $\text{kg}^{-1}$  mannitol, 300 - 900 mOsmoles  $\text{kg}^{-1}$  sucrose with 0 - 0.5 mM KCl, 300 - 900 mOsmoles  $\text{kg}^{-1}$  sucrose/KCl (1:1 ratio), and 300 - 900 mOsmoles  $\text{kg}^{-1}$  KCl. All the osmotica contained 0.5 mM  $\text{CaSO}_4$ .

Only a single beet disc was required for each experiment. The selected disc was secured to a perspex sample holder and covered in 5 ml of silicone oil. Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) measurements were made under oil every 5 - 10 minutes for a maximum of 2 hours (after Tomos and Wyn Jones, 1988).

**Plate 5.1, Sugar beet plants eight weeks after germination**





## 5.3, Results

### 5.3.1, Turgor regulation in an open system

The cell pressure probe and picolitre osmometry were used to measure turgor regulation and osmotic adjustment in sugar beet taproot discs aerated in 0 - 600 mM mannitol-0.5 mM CaSO<sub>4</sub> osmotica over 7 days (Figure 5.3 and 5.4). Sugar beet taproot discs in 0 mM mannitol-0.5 mM CaSO<sub>4</sub> had an initial (day 0) turgor pressure ( $P_{\text{cell}}$ ) of 1.12 MPa, decreasing to 0.85 MPa after 48 hours (day 2). Turgor pressure was maintained at this level until the experiment terminated at day 7. The turgor pressure ( $P_{\text{cell}}$ ) in beet discs in 300 mM mannitol-0.5 mM CaSO<sub>4</sub> remained constant at around 0.65 MPa, this  $P_{\text{cell}}$  value corresponds to  $P_{\text{cell}}$  in intact, mature sugar beet taproots *in vivo* (see Tomos *et al.*, 1992). Sugar beet discs aerated in 600 mM mannitol-0.5 mM CaSO<sub>4</sub> had an initial turgor pressure ( $P_{\text{cell}}$ ) of 0.24 MPa which increased to a new steady value of 0.42 MPa within 48 hours (Figure 5.3).

Changes in turgor pressure ( $P_{\text{cell}}$ ) were accompanied by corresponding changes in cell osmotic pressure (Figure 5.4). Beet discs in 300 mM mannitol-0.5 mM CaSO<sub>4</sub> maintained an osmotic pressure ( $\Pi_{\text{cell}}$ ) of 1.95 MPa throughout the experiment (this corresponds to  $\Pi_{\text{cell}}$  in intact, mature sugar beet tissue *in vivo* - Tomos *et al.*, 1992). Discs aerated in 0 mM mannitol-0.5 mM CaSO<sub>4</sub> had an initial  $\Pi_{\text{cell}}$  of 1.59 MPa, decreasing to 1.24 MPa within 48 hours (day 2), while  $\Pi_{\text{cell}}$  in beet discs in 600 mM mannitol-0.5 mM CaSO<sub>4</sub> increased from 2.0 MPa to 2.26 MPa within the same time period (Figure 5.4). The difference between turgor pressure ( $\Delta P_{\text{cell}}$ ) at day 0 and day 7 and osmotic pressure ( $\Delta \Pi_{\text{cell}}$ ) at day 0 and day 7 is shown in Table 5.1. There is excellent agreement between  $\Delta P_{\text{cell}}$  and  $\Delta \Pi_{\text{cell}}$ , indicating that turgor regulation in sugar beet taproot discs, in an open system, is due to osmotic adjustment of solutes in the protoplast, and confirming that the reflection coefficient of these cells is in fact 1.



**Table 5.1,  $\Delta P_{\text{cell}}$  and  $\Delta \Pi_{\text{cell}}$  (MPa) in sugar beet taproot discs, between day 0 and day 7, under open system conditions**

<b>Mannitol (mM)</b>	<b><math>\Delta P_{\text{cell}}</math> (MPa)</b>	<b><math>\Delta \Pi_{\text{cell}}</math> (MPa)</b>
<b>0</b>	<b>-0.33</b>	<b>-0.37</b>
<b>300</b>	<b>-0.06</b>	<b>-0.15</b>
<b>600</b>	<b>0.23</b>	<b>0.22</b>



### 5.3.2, Turgor regulation in a closed system

Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) of freshly cut and pre-treated sugar beet discs, water saturated silicone oil, were measured at 5 - 10 minute intervals for a maximum of 2 hours. Freshly cut, unrinsed sugar beet taproot discs in silicone oil had an initial turgor pressure ( $P_{\text{cell}}$ ) of around 0.35 MPa, this is lower than  $P_{\text{cell}}$  in the intact taproot (see Tomos *et al.*, 1992) due to the broken cell solutes in the apoplast. After a lag of approximately 20 minutes,  $P_{\text{cell}}$  was regulated upwards, reaching 0.6 - 0.7 MPa after 40 minutes (Figure 5.5). This corresponds to  $P_{\text{cell}}$  in the intact taproot *in vivo* (Tomos *et al.*, 1992). Turgor pressure was maintained at this level until the discs became anaerobic 3 - 4 hours later (data not shown). There was no corresponding increase in cell osmotic pressure,  $\Pi_{\text{cell}}$  was maintained at around 2.4 MPa throughout, indicating that turgor pressure is regulated by adjustment of solutes in the apoplast rather than adjustment of solutes in the protoplast (Figure 5.6).

Pre-treating beet discs in an aqueous osmoticum, prior to covering the tissue in water saturated silicone oil, flushes out the original free apoplastic solutes and replaces them with the solutes present in the osmoticum. The concentrations of the osmotica used were largely determined by the osmotica used in the open system experiment (see Figure 5.3 and 5.4). All the osmotica were made up using 0.5 mM  $\text{CaSO}_4$  stock solution.

Pre-treatment in 600 mOsmoles  $\text{kg}^{-1}$  sucrose and/or KCl (Figure 5.7) resulted in an initial  $P_{\text{cell}}$  of around 0.4 MPa. After a lag of between 20 - 30 minutes  $P_{\text{cell}}$  was regulated upwards, reaching 0.7 MPa (which corresponds to  $P_{\text{cell}}$  in the intact taproot) within 40 - 60 minutes. Turgor pressure ( $P_{\text{cell}}$ ) was maintained at this level for the duration of the experiment. In the presence of apoplastic KCl turgor regulation is indistinguishable from that observed in the freshly cut beet tissue in Figure 5.5 and 5.6; the target  $P_{\text{cell}}$  was achieved within 40 minutes (after a lag of 20 minutes). However, in the absence of apoplastic KCl, beet discs under closed system conditions, took about 20 minutes longer to achieve the target  $P_{\text{cell}}$  value; beet discs pre-treated in the sucrose only osmoticum reached a  $P_{\text{cell}}$  of 0.7 MPa within 60 minutes (after a lag of 30 minutes).



Osmotic pressure ( $\Pi_{\text{cell}}$ ) was maintained at around 2.5 MPa throughout the experiment, indicating that osmotic adjustment, leading to turgor regulation, is apoplastic rather than protoplasmic in nature.

This turgor regulation mechanism in the presence of apoplastic sucrose and/or KCl is demonstrated again in **Figure 5.9**. Sugar beet discs pre-treated in 900 mOsmoles  $\text{kg}^{-1}$  sucrose and/or KCl undergo cell plasmolysis due to the magnitude of the osmotic pressure step across the plasma membrane. Turgor pressure ( $P_{\text{cell}}$ ) recovered sufficiently to be measured reliably within 20 - 40 minutes, reaching 0.7 MPa within 60 - 80 minutes. Once again, beet discs pre-treated in osmotica containing KCl reached the target  $P_{\text{cell}}$  20 minutes earlier than the beet discs pre-treated in the sucrose only osmoticum.

Pre-treatment in 300 mOsmoles  $\text{kg}^{-1}$  sucrose and/or KCl (**Figure 5.10 and 5.11**) resulted in constant turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) values of around 0.7 MPa and 2.2 MPa respectively ( $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  did not deviate from these values for the duration of the time course). These data largely correspond to  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  *in vivo* (see Tomos *et al.*, 1992) and also correspond to  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  in open system beet tissue in 300 mM mannitol-0.5 mM  $\text{CaSO}_4$  (**Figure 5.3 and 5.4**).

In order to obtain closed system data which could be directly comparable to the open system data (**Figure 5.3 and 5.4**), beet discs were pre-treated in the open system mannitol osmotica, prior to being covered in silicone oil. The 0 mM mannitol-0.5 mM  $\text{CaSO}_4$  pre-treated beet discs underwent a rapid increase in turgor pressure (relative to  $P_{\text{cell}}$  *in vivo*), to 1.1 MPa (**Figure 5.12**). Turgor pressure was maintained at this level for the duration of the experiment. This increase in  $P_{\text{cell}}$  did not induce a rapid downward turgor regulation mechanism in this case. Osmotic pressure ( $\Pi_{\text{cell}}$ ) remained constant at 1.6 MPa throughout (**Figure 5.13**). These data are comparable to  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  in the open system 0 mM mannitol-0.5 mM  $\text{CaSO}_4$  beet discs at day 0. A 300 mM mannitol-0.5 mM  $\text{CaSO}_4$  pre-treatment (**Figure 5.14 and 5.15**) resulted in constant  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  values of 0.7 MPa and 2.2 MPa respectively. These values correspond to  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  in the equivalent open system beet discs at day 0 to day 7, and also correspond



to  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  in the intact, mature taproot *in vivo* (see Tomos *et al.*, 1992). A 600 mM mannitol-0.5 mM  $\text{CaSO}_4$  pre-treatment resulted in  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  values of 0.3 MPa and 2.5 MPa respectively. Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) were maintained at constant levels throughout the time course. Once again  $P_{\text{cell}}$  and  $\Pi_{\text{cell}}$  correspond to the values obtained in the equivalent open system treatment at day 0. It is assumed that turgor regulation was not achieved due to the impermeant (or slowly permeant) nature of mannitol.



**Figure 5.3 and 5.4, Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in aged sugar beet taproot discs (open system)**

Changes in turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in sugar beet discs aerated in 0 - 600 mM mannitol-0.5 mM  $\text{CaSO}_4$  for 7 days. Data are presented as mean and standard deviation, n is 15 (5 beet discs, 3 cells per disc).

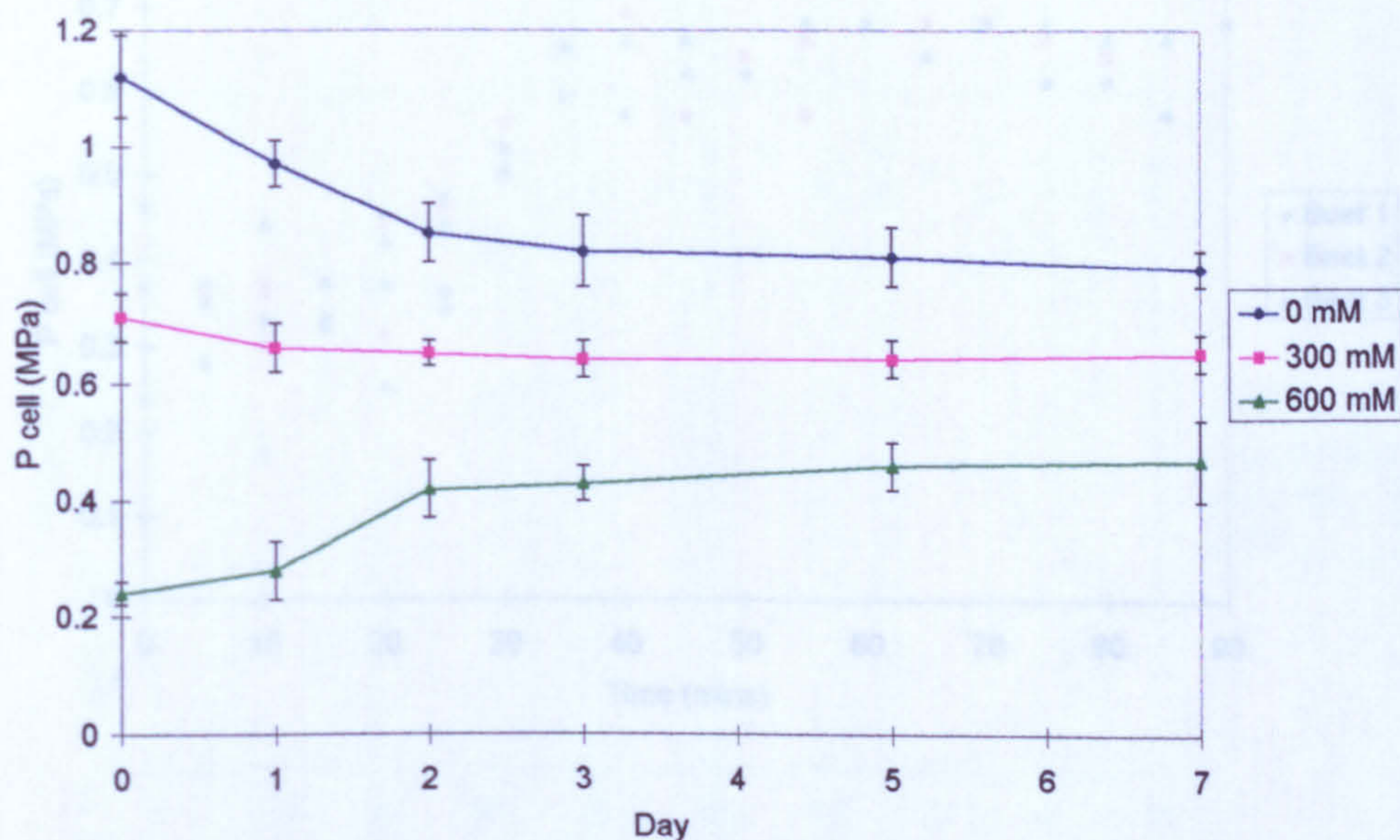
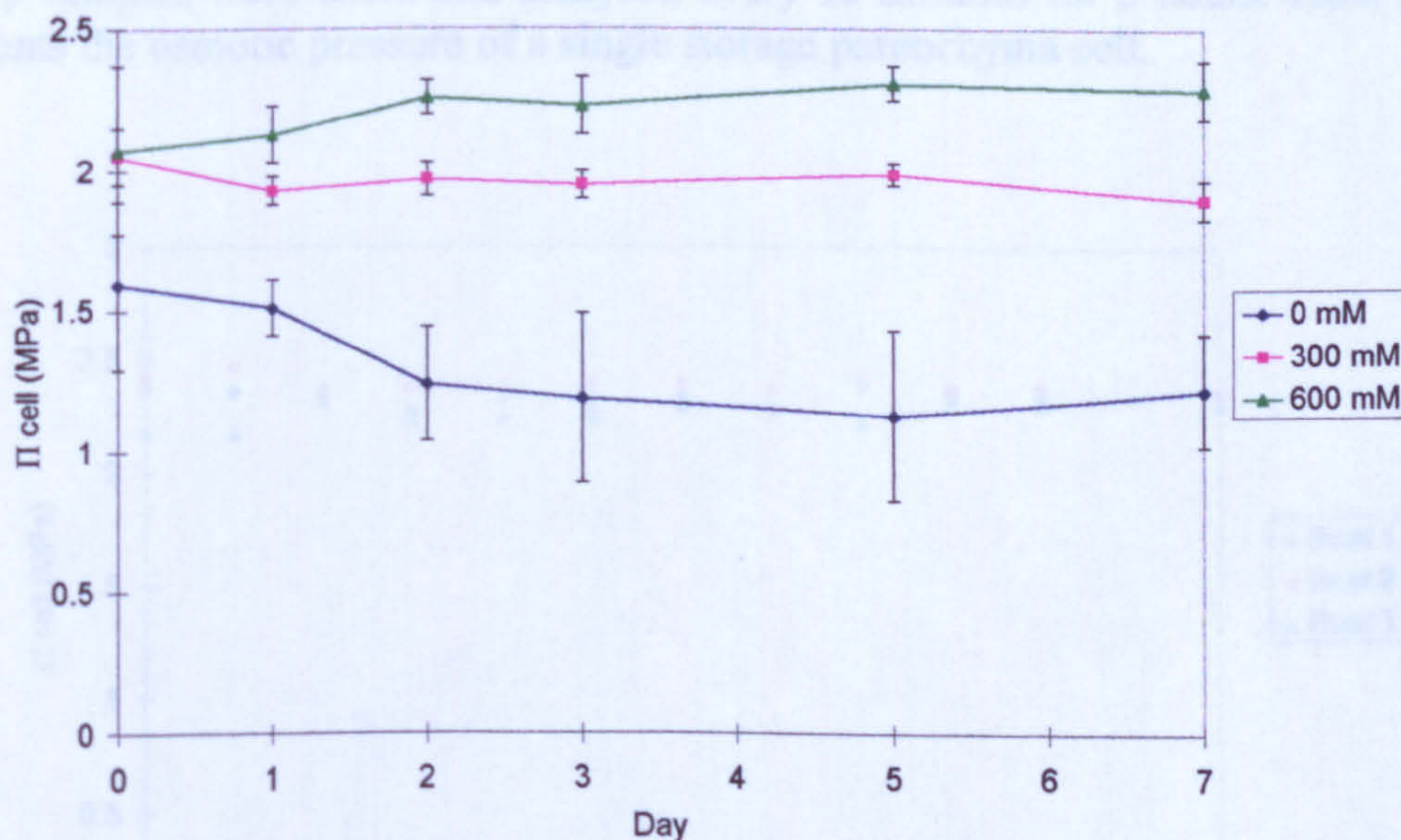


Figure 5.4, Osmotic pressure ( $\Pi_{\text{cell}}$ ) in freshly cut sugar beet taproot discs under glucose oil (closed system)

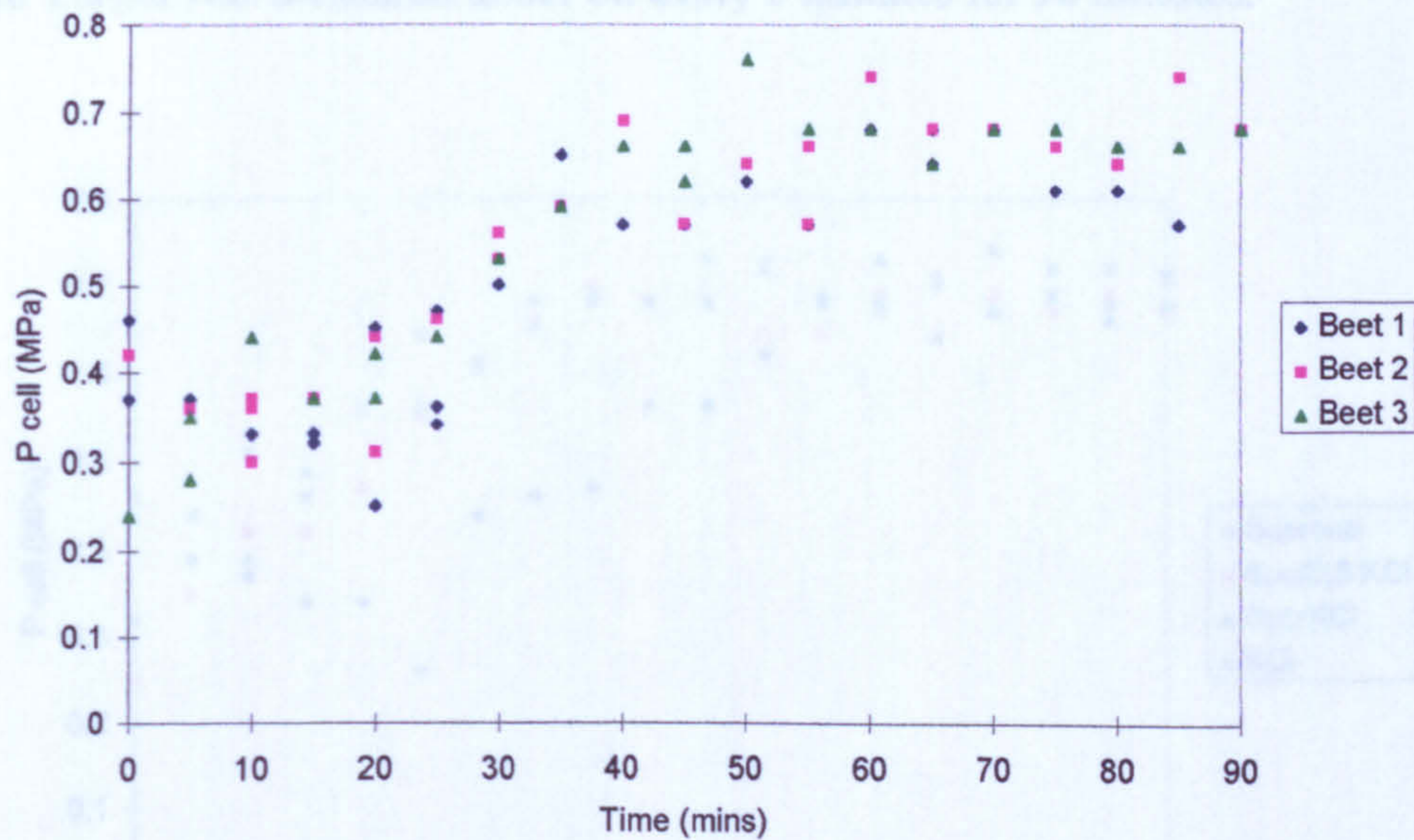
Osmotic pressure ( $\Pi_{\text{cell}}$ ) in freshly cut sugar beet taproot discs under glucose oil. Single cell sap samples were taken and analysed every 10 minutes for 2 hours. Each symbol represents the osmotic pressure of a single storage parenchyma cell.





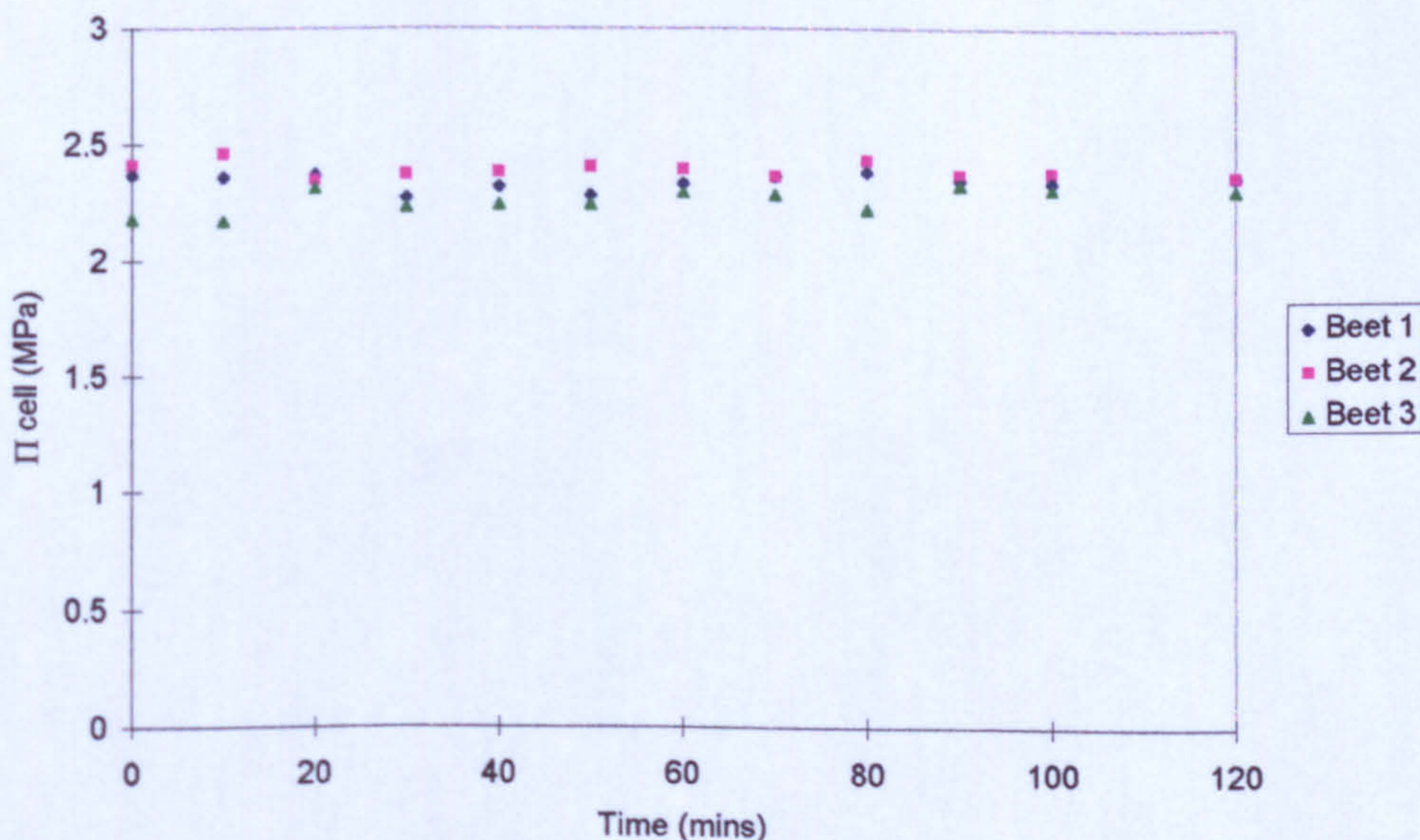
**Figure 5.5, Turgor pressure ( $P_{\text{cell}}$ ) in freshly cut sugar beet taproot discs under silicone oil (closed system)**

Turgor pressure ( $P_{\text{cell}}$ ) in freshly cut sugar beet taproot discs under silicone oil. Turgor pressure was measured at 5 minute intervals for 90 minutes. Each symbol represents a single turgor pressure measurement from a single storage parenchyma cell.



**Figure 5.6, Osmotic pressure ( $\Pi_{\text{cell}}$ ) in freshly cut sugar beet taproot discs under silicone oil (closed system)**

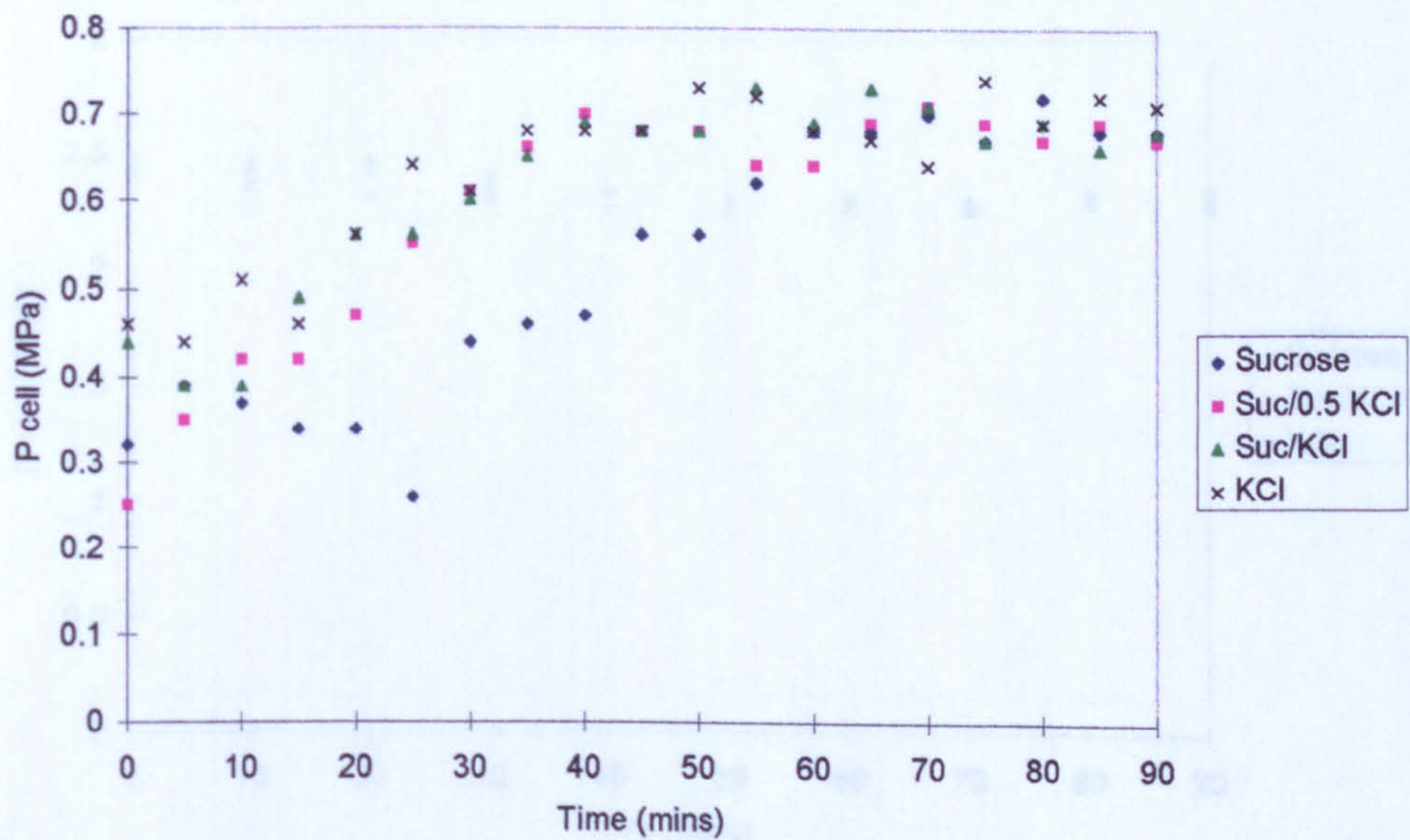
Osmotic pressure ( $\Pi_{\text{cell}}$ ) in freshly cut sugar beet taproot discs under silicone oil. Single cell sap samples were taken and analysed every 10 minutes for 2 hours. Each symbol represents the osmotic pressure of a single storage parenchyma cell.





**Figure 5.7, Turgor pressure ( $P_{\text{cell}}$ ) in sugar beet taproot discs pre-treated in 600 mOsmoles  $\text{kg}^{-1}$  sucrose and/or KCl (closed system)**

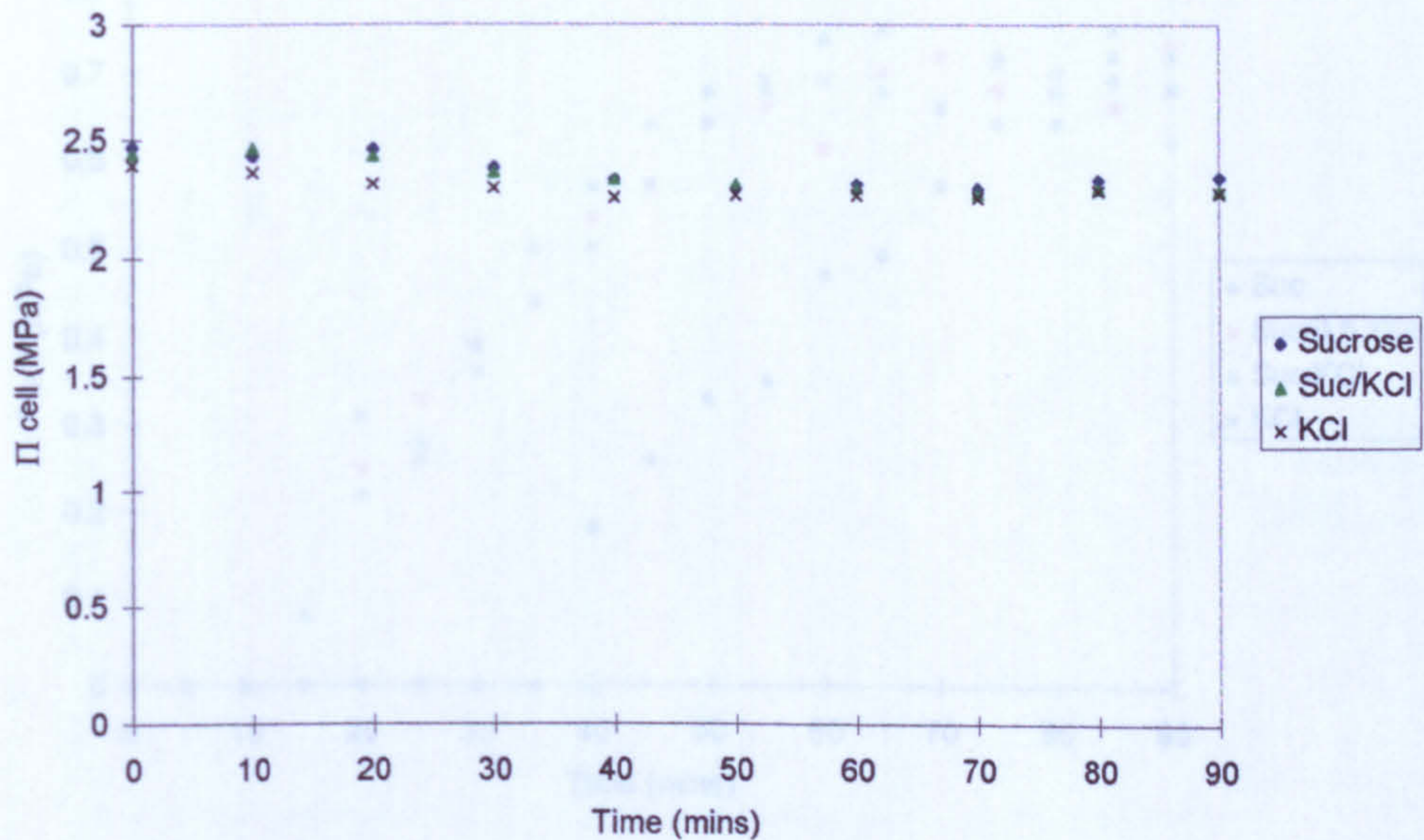
Turgor pressure ( $P_{\text{cell}}$ ) in sugar beet discs aerated in either 600 mOsmoles  $\text{kg}^{-1}$  sucrose, 600 mOsmoles  $\text{kg}^{-1}$  sucrose with 0.5 mM KCl, 600 mOsmoles  $\text{kg}^{-1}$  sucrose/KCl (300 mOsmoles  $\text{kg}^{-1}$  of each), or 600 mOsmoles  $\text{kg}^{-1}$  KCl for 15 minutes prior to covering in silicone oil. All the pre-treatment osmotica were made up using 0.5 mM  $\text{CaSO}_4$  solution. Turgor was measured under oil every 5 minutes for 90 minutes.





**Figure 5.8, Osmotic pressure ( $\Pi_{\text{cell}}$ ) in sugar beet taproot discs pre-treated in 600 mOsmoles  $\text{kg}^{-1}$  sucrose and/or KCl (closed system)**

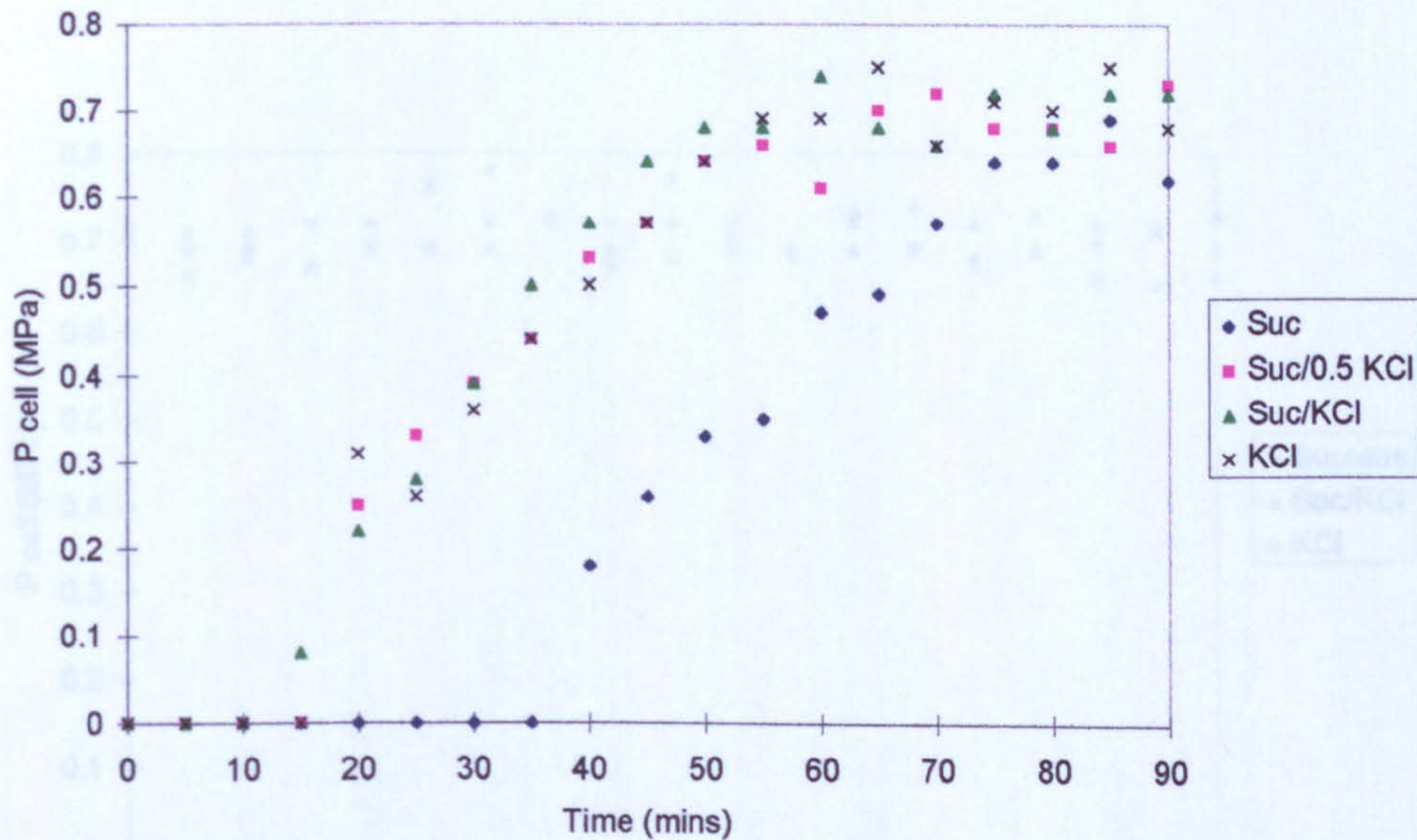
Osmotic pressure ( $\Pi_{\text{cell}}$ ) in sugar beet discs aerated in either 600 mOsmoles  $\text{kg}^{-1}$  sucrose, 600 mOsmoles  $\text{kg}^{-1}$  sucrose/KCl (300 mOsmoles  $\text{kg}^{-1}$  of each), or 600 mOsmoles  $\text{kg}^{-1}$  KCl for 15 minutes prior to covering in silicone oil. All the pre-treatment osmotica were made up using 0.5 mM  $\text{CaSO}_4$  solution. Osmotic pressure was measured under oil every 10 minutes for 90 minutes.





**Figure 5.9, Turgor pressure ( $P_{\text{cell}}$ ) in sugar beet taproot discs pre-treated in 900 mOsmoles  $\text{kg}^{-1}$  sucrose and/or KCl (closed system)**

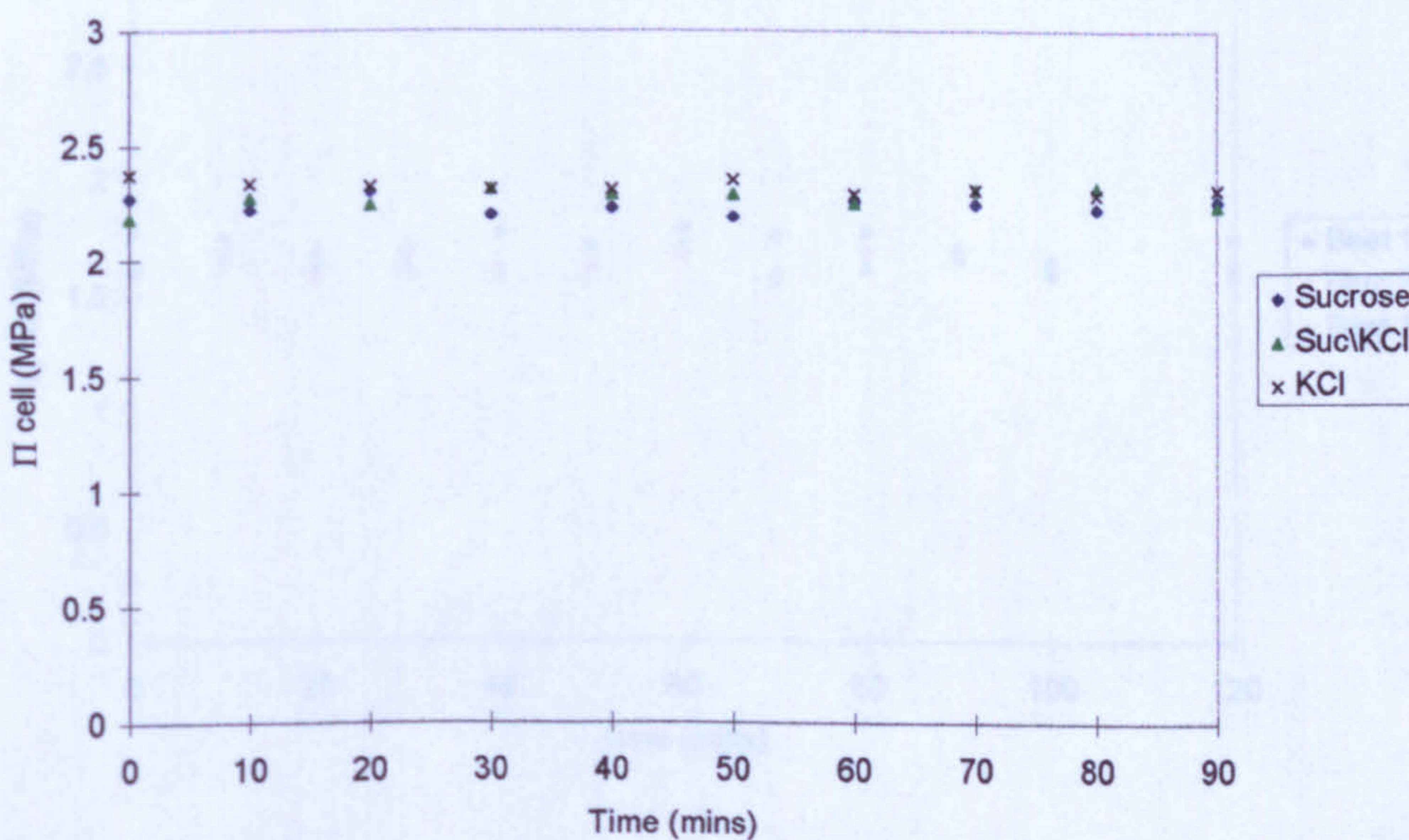
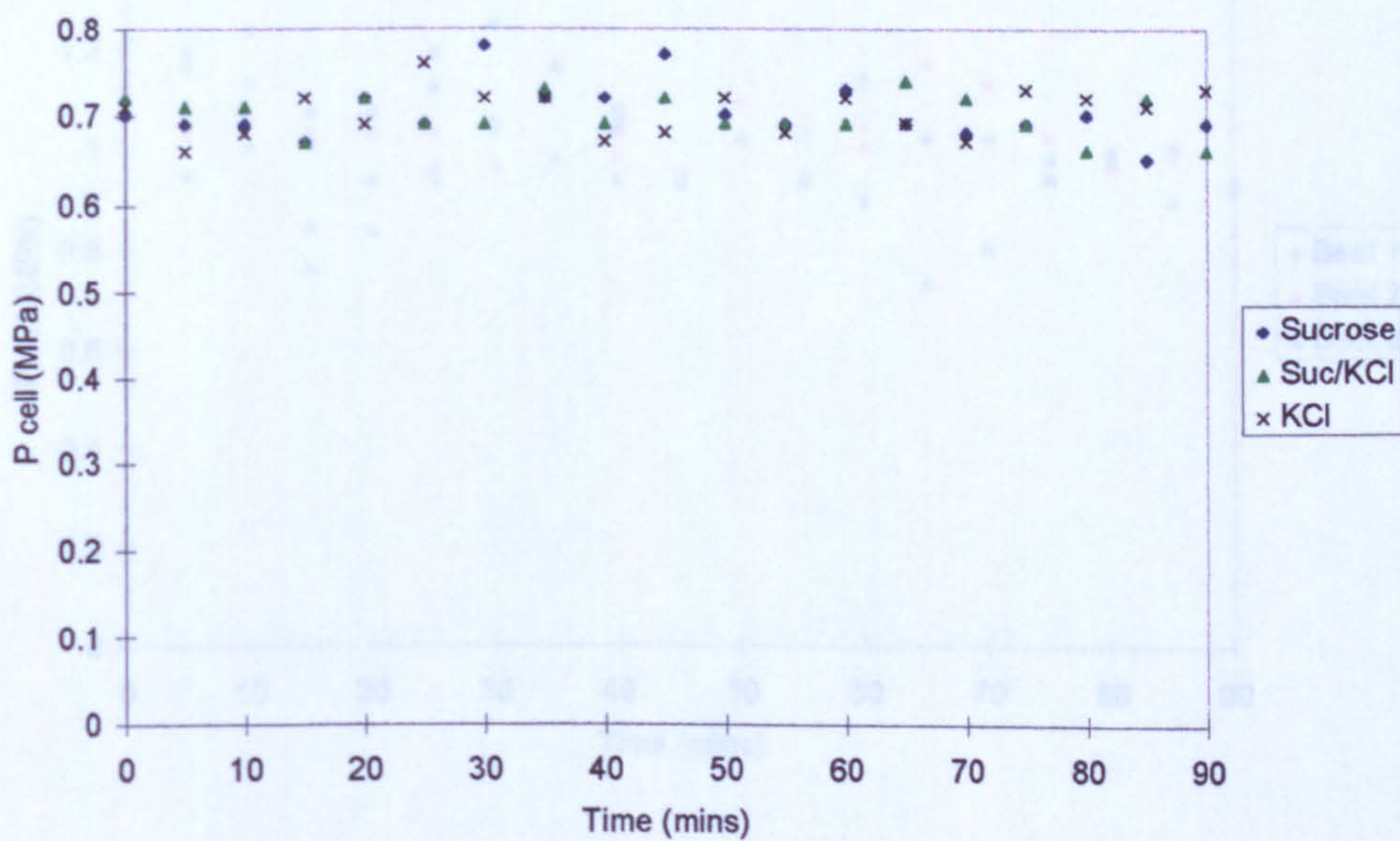
Turgor pressure ( $P_{\text{cell}}$ ) in sugar beet discs aerated in either 900 mOsmoles  $\text{kg}^{-1}$  sucrose, 900 mOsmoles  $\text{kg}^{-1}$  sucrose with 0.5 mM KCl, 900 mOsmoles  $\text{kg}^{-1}$  sucrose/KCl (450 mOsmoles  $\text{kg}^{-1}$  of each), or 900 mOsmoles  $\text{kg}^{-1}$  KCl for 15 minutes prior to covering in silicone oil. All the pre-treatment osmotica were made up using 0.5 mM  $\text{CaSO}_4$  solution. Turgor was measured under oil every 5 minutes for 90 minutes.





**Figure 5.10 and 5.11, Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in sugar beet taproot discs pre-treated in 300 mOsmoles  $\text{kg}^{-1}$  sucrose and/or KCl (closed system)**

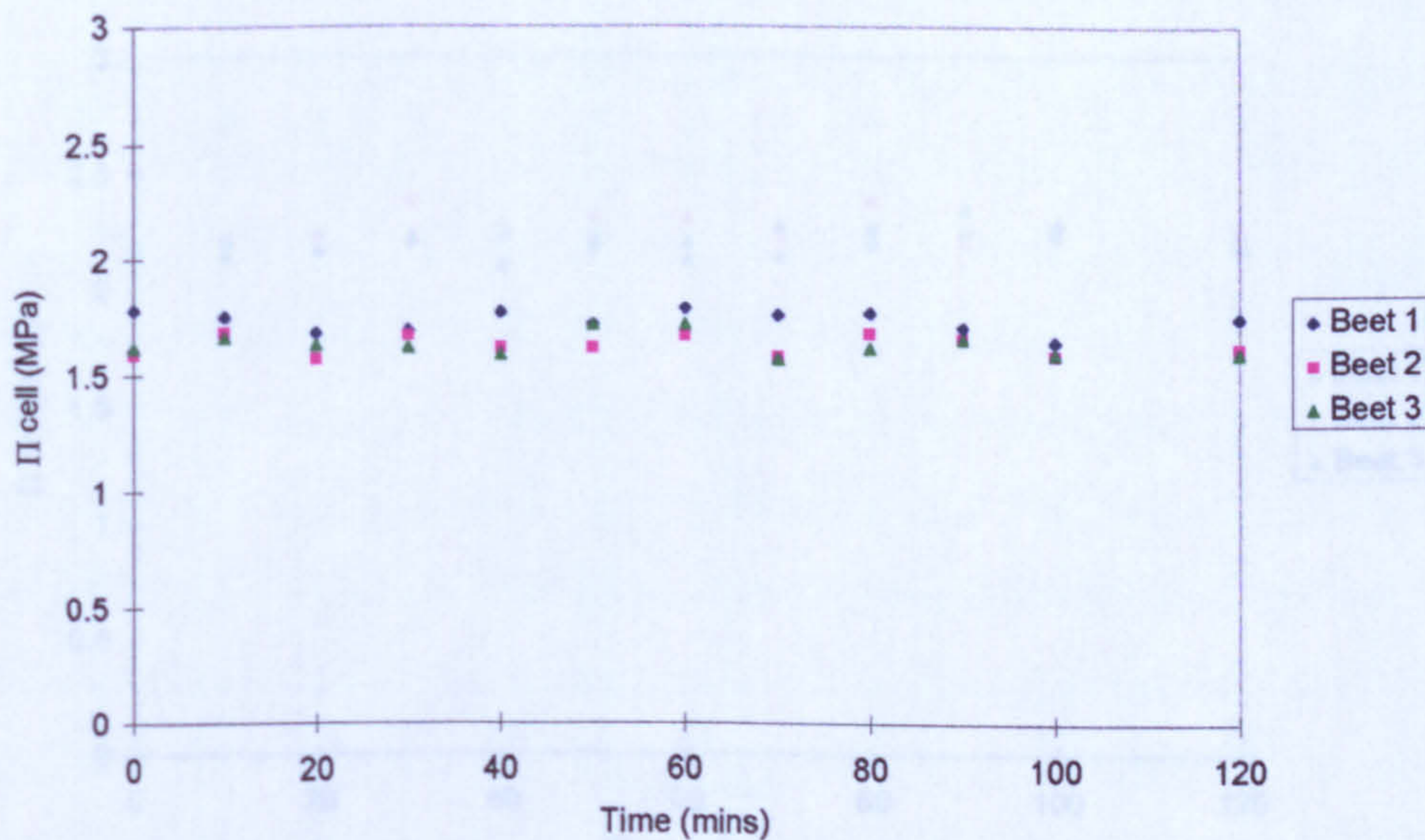
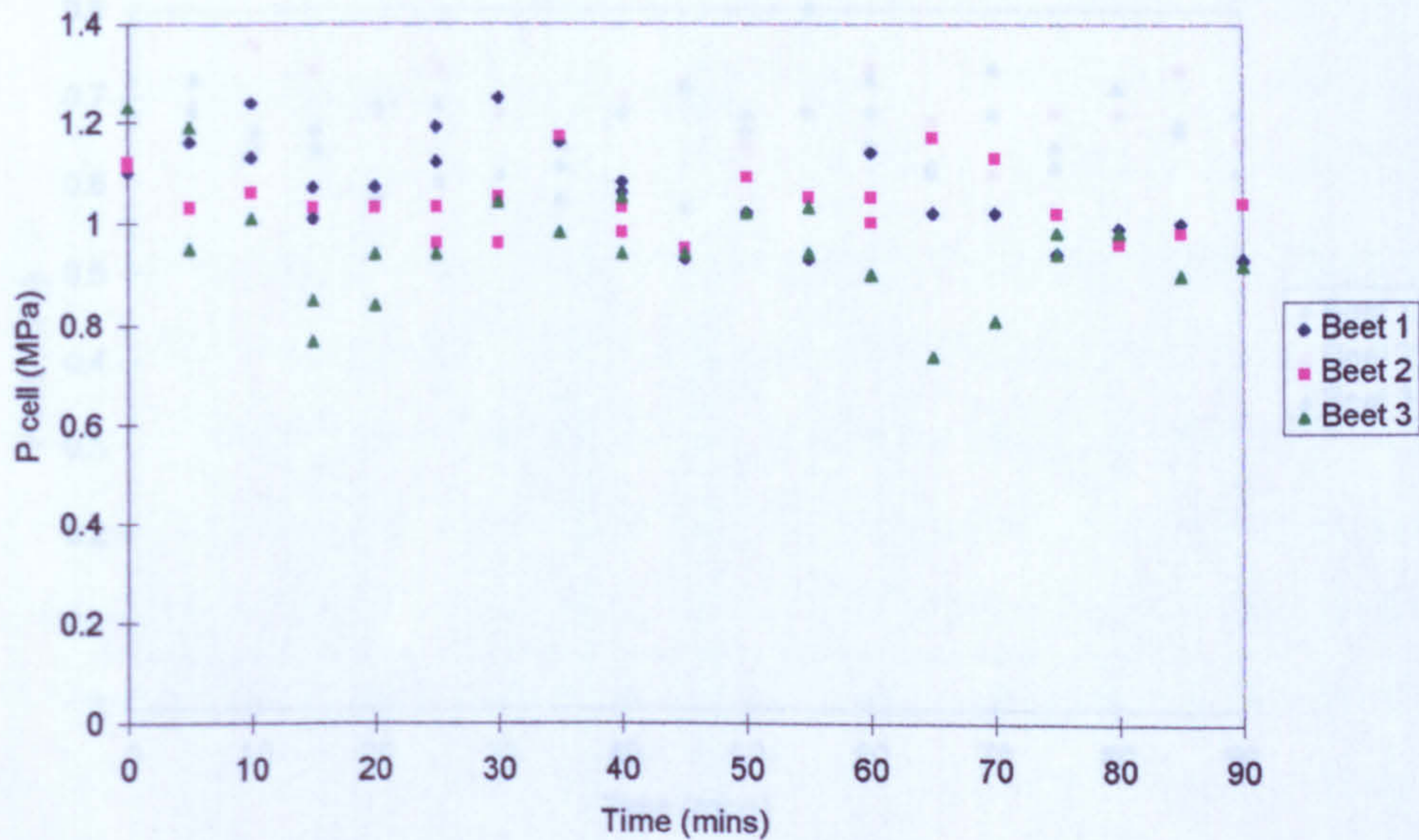
Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in sugar beet discs aerated in either 300 mOsmoles  $\text{kg}^{-1}$  sucrose, 300 mOsmoles  $\text{kg}^{-1}$  sucrose/KCl (150 mOsmoles  $\text{kg}^{-1}$  of each), or 300 mOsmoles  $\text{kg}^{-1}$  KCl for 15 minutes prior to covering in silicone oil. All the pre-treatment osmotica were made up using 0.5 mM  $\text{CaSO}_4$  solution. Turgor pressure and osmotic pressure were measured under oil every 5 and 10 minutes respectively, for 90 minutes.





**Figure 5.12 and 5.13, Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in sugar beet taproot discs pre-treated in 0 mM mannitol-0.5 mM  $\text{CaSO}_4$  (closed system)**

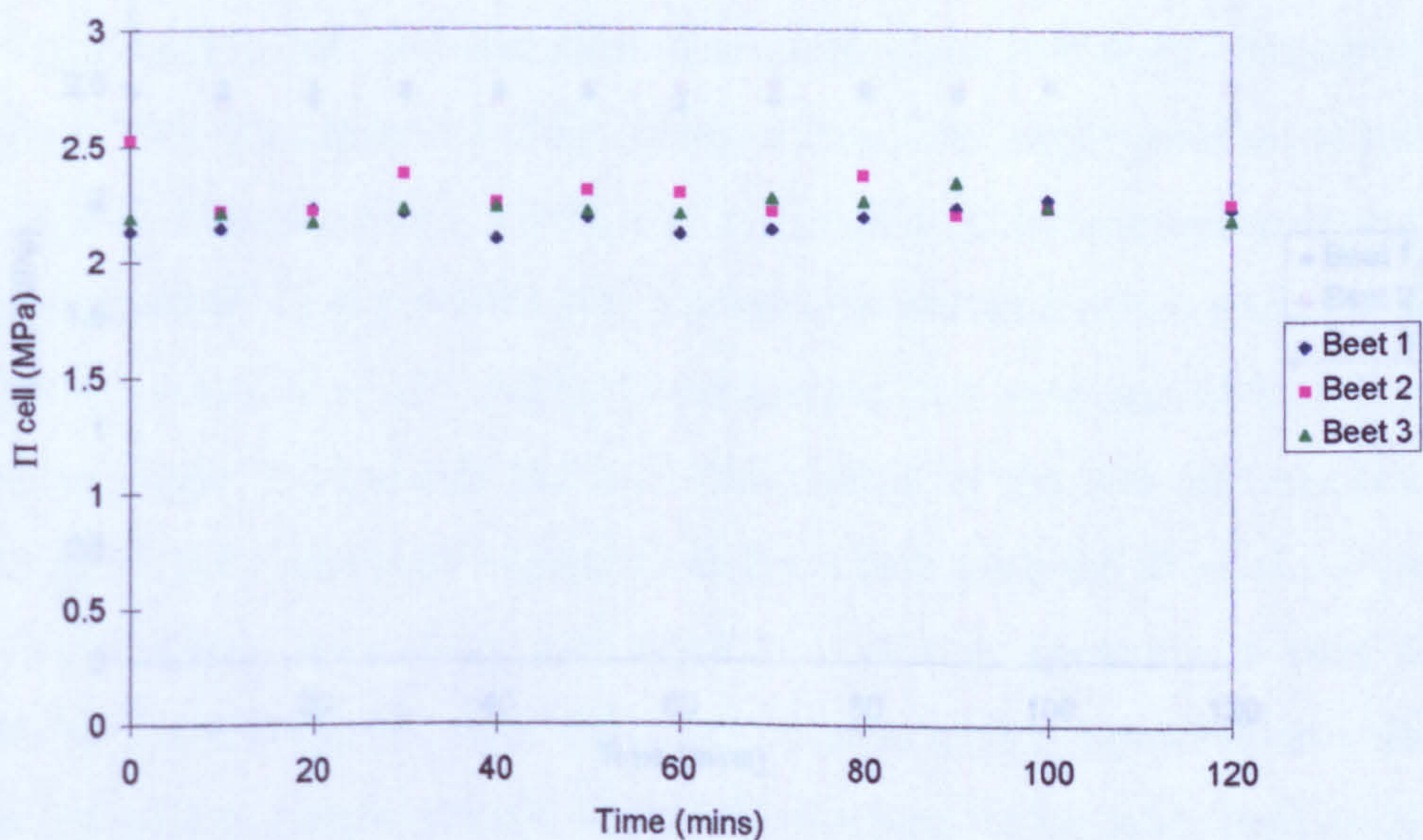
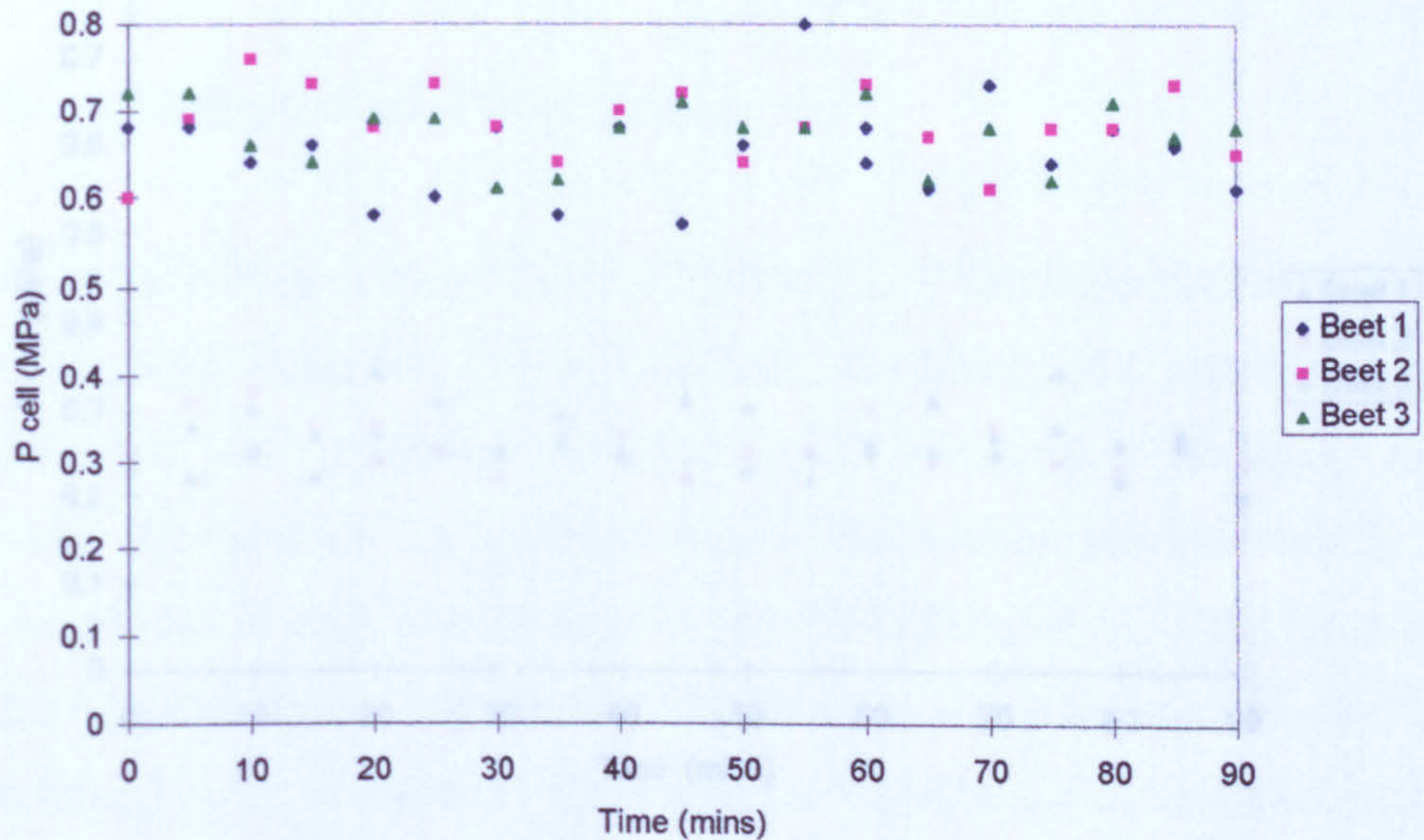
Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in sugar beet taproot discs pre-treated in 0 mM mannitol-0.5 mM  $\text{CaSO}_4$  for 15 minutes prior to covering in silicone oil. Turgor pressure and osmotic pressure were measured at 5 and 10 minute intervals respectively, for a maximum of 2 hours.





**Figure 5.14 and 5.15, Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in sugar beet taproot discs pre-treated in 300 mM mannitol-0.5 mM  $\text{CaSO}_4$  (closed system)**

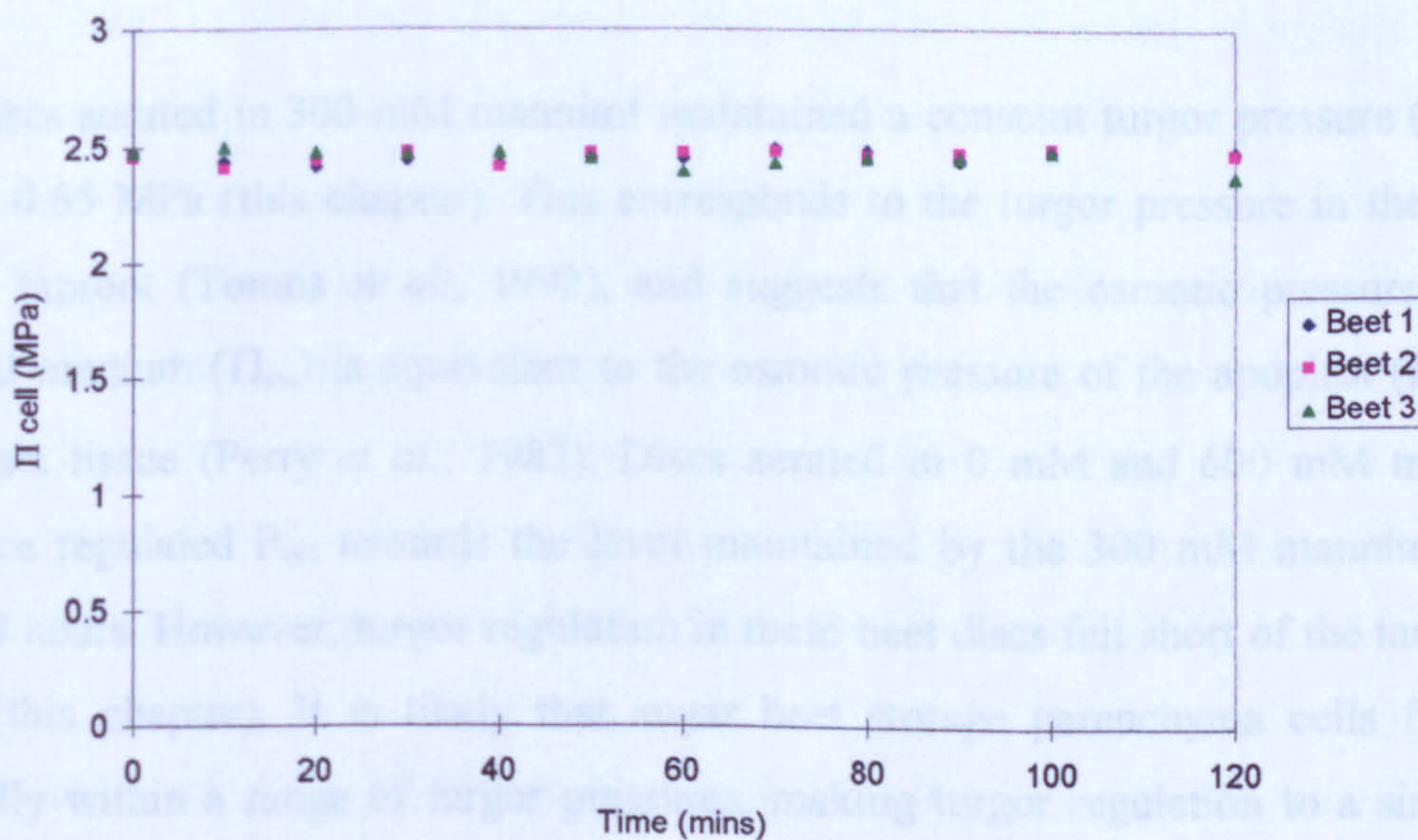
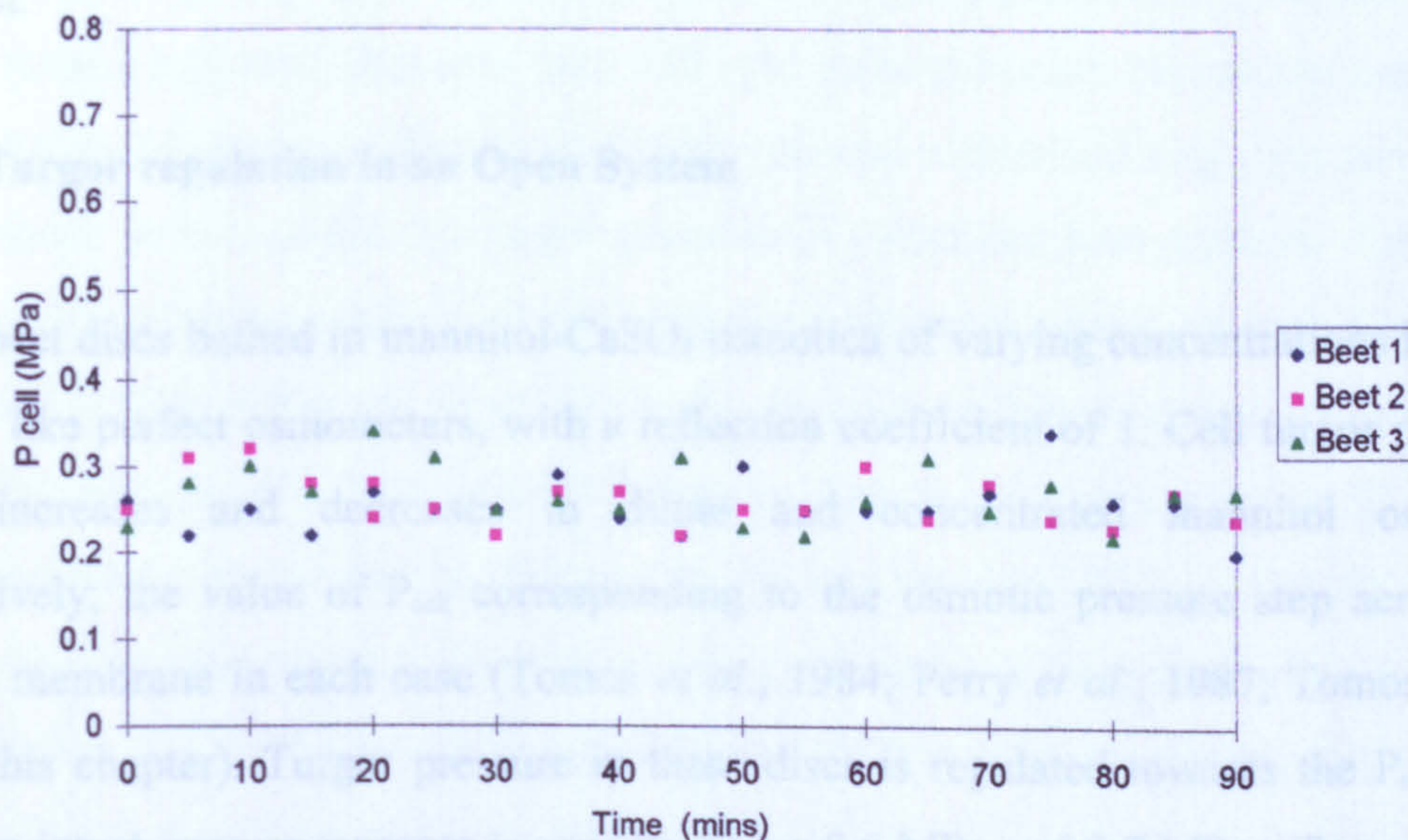
Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in sugar beet taproot discs pre-treated in 300 mM mannitol-0.5 mM  $\text{CaSO}_4$  for 15 minutes prior to covering in silicone oil. Turgor pressure and osmotic pressure were measured at 5 and 10 minute intervals respectively, for a maximum of 2 hours.





**Figure 5.16 and 5.17, Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in sugar beet taproot discs pre-treated in 600 mM mannitol-0.5 mM  $\text{CaSO}_4$  (closed system)**

Turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) in sugar beet taproot discs pre-treated in 600 mM mannitol-0.5 mM  $\text{CaSO}_4$  for 15 minutes prior to covering in silicone oil. Turgor pressure and osmotic pressure were measured at 5 and 10 minute intervals respectively, for a maximum of 2 hours.





## 5.4, Discussion

The data presented in this chapter demonstrates that sugar beet taproot discs in an open system regulate cell turgor pressure by adjustment of solutes in the protoplast over 48 hours. Whereas beet discs in a closed system environment apparently regulate cell turgor pressure (in one direction) by rapid and subtle adjustment of solutes in the apoplast.

### 5.4.1, Turgor regulation in an Open System

Sugar beet discs bathed in mannitol- $\text{CaSO}_4$  osmotica of varying concentrations initially behave like perfect osmometers, with a reflection coefficient of 1. Cell turgor pressure ( $P_{\text{cell}}$ ) increases and decreases in dilute and concentrated mannitol osmotica respectively; the value of  $P_{\text{cell}}$  corresponding to the osmotic pressure step across the plasma membrane in each case (Tomos *et al.*, 1984; Perry *et al.*, 1987; Tomos *et al.*, 1992; this chapter). Turgor pressure in these discs is regulated towards the  $P_{\text{cell}}$  level found in intact, mature taproots *in vivo* (between 0.6 MPa and 0.7 MPa - Tomos *et al.*, 1992), within 48 hours (Figure 5.3 and 5.4). After 48 hours  $P_{\text{cell}}$  is maintained at a constant level for up to 7 days (this chapter).

Beet discs aerated in 300 mM mannitol maintained a constant turgor pressure ( $P_{\text{cell}}$ ) of around 0.65 MPa (this chapter). This corresponds to the turgor pressure in the intact, mature taproot (Tomos *et al.*, 1992), and suggests that the osmotic pressure of the external medium ( $\Pi_{\text{ext}}$ ) is equivalent to the osmotic pressure of the apoplast ( $\Pi_{\text{wall}}$ ) in the intact tissue (Perry *et al.*, 1987). Discs aerated in 0 mM and 600 mM mannitol osmotica regulated  $P_{\text{cell}}$  towards the level maintained by the 300 mM mannitol discs over 48 hours. However, turgor regulation in these beet discs fell short of the target  $P_{\text{cell}}$  value (this chapter). It is likely that sugar beet storage parenchyma cells function optimally within a range of turgor pressures, making turgor regulation to a single set point unnecessary and metabolically expensive. It is also important to consider that beet discs in an open system are in a completely artificial and alien environment which affects the physiology and biochemistry of the cell (Van Steveninck, 1975).



Changes in turgor pressure ( $P_{\text{cell}}$ ) were accompanied by corresponding changes in cell osmotic pressure ( $\Pi_{\text{cell}}$ ), demonstrating that  $P_{\text{cell}}$  regulation is achieved by adjustment of solutes in the protoplast (this chapter). Adjustment of apoplastic solutes would be impossible in an open system as the apoplastic volume is effectively equivalent to the volume of osmoticum surrounding the discs (which is 5 litres in this case).

Perry *et al.*, in 1987, described a similar adjustment mechanism in red beet taproot tissue aerated in 0 mM, 200 mM, and 350 mM mannitol (each osmoticum containing 0.5 mM  $\text{CaSO}_4$ ). Red beet discs in 200 mM mannitol maintained turgor pressure at 0.5 MPa, which is comparable to turgor pressure in intact red beet taproots (Leigh and Tomos, 1983). Red beet discs in 0 mM mannitol underwent a decrease in  $P_{\text{cell}}$  from 0.88 MPa to 0.7 MPa within 48 hours, while  $P_{\text{cell}}$  in discs in 350 mM mannitol increased from 0.12 MPa to 0.31 MPa within 48 hours. Changes in turgor pressure ( $P_{\text{cell}}$ ) were accompanied by corresponding changes in osmotic pressure ( $\Pi_{\text{cell}}$ ). The decrease in  $\Pi_{\text{cell}}$  in the 0 mM mannitol red beet discs was found to be due to solute efflux out of the cell. The increase in  $\Pi_{\text{cell}}$  in red beet discs aerated in 350 mM mannitol was found to be due to sucrose hydrolysis, subsequently leading to an increase in the total sugar content of the cell.

Aerating plant tissue in an open system is referred to as washing or ageing. Ageing induces profound physiological and biochemical changes within the cell, most notably rapid increases in protein synthesis and respiration, followed by an increase in solute uptake (for reviews see Van Steveninck, 1975; Poole, 1976). In sugar beet and red beet taproot tissue, the ageing phenomenon induces vacuolar acid-invertase activity (Bacon *et al.*, 1965; Leigh *et al.*, 1979; Milling *et al.*, 1993; Marvier *et al.*, 1997). Induction of acid-invertase activity coincides with a decrease in sucrose concentration and accumulation of reducing sugars (Leigh *et al.*, 1979, Perry *et al.*, 1987).

Acid-invertase activity is undetectable in freshly cut beet tissue. Induction of activity occurs after 24 hours, and is maximal after 72 hours (Milling *et al.*, 1993; Marvier *et al.*, 1997). Marvier *et al.* (1997) detected a maximum acid-invertase activity of 0.12  $\mu\text{mol.sucrose hydrolysed min}^{-1} \text{mg}^{-1}$  in red beet taproot discs after 72 hours of ageing.



Initially the rate of sucrose decline was dependent on the concentration of the external medium ( $\Pi_{ext}$ ). Perry *et al.* (1987) found that, during the first 24 hours, the decrease in sucrose concentration was greatest in discs aerated in 0 mM mannitol and slowest in discs aerated in 350 mM mannitol. However, after 24 hours sucrose concentration decreased at a constant rate of 3.5 mM h<sup>-1</sup> in all treatments. Sucrose had disappeared from discs in 0 mM mannitol after 46 hours and from all other treatments by 118 hours. This decrease in sucrose concentration was accompanied by an accumulation of reducing sugars (glucose and fructose). Accumulation of glucose and fructose began after a lag of 24 hours and increased steadily at a rate of 4.4 mM h<sup>-1</sup> before reaching a plateau after 50 hours. The final concentration of reducing sugars was dependent on the concentration of the external medium. After 118 hours (approximately 5 days) of ageing, red beet discs in 0 mM, 200 mM and 350 mM mannitol had 85 mM, 126 mM, and 167 mM reducing sugars respectively.

In the open system described above turgor regulation can only be achieved by osmotic adjustment of the protoplast. Uptake of mannitol from the external medium occurs only very slowly due to its largely impermeant nature (Cram, 1984; Perry *et al.*, 1987). Perry *et al.* (1987) demonstrated that the solutes necessary for turgor regulation, in open system beet discs, originate from the protoplast itself; hydrolysis of sucrose induced by the ageing phenomenon provides hexoses that can be used to regulate turgor pressure. The final concentration of reducing sugars (hexoses) is dependent on the concentration of the external medium ( $\Pi_{ext}$ ), which in this case is also the concentration of the apoplast ( $\Pi_{wall}$ ). Modification of cell osmotic pressure ( $\Pi_{cell}$ ) by accumulation (or loss) of reducing sugars directly influences the turgor pressure ( $P_{cell}$ ) of the cell (Perry *et al.*, 1987).

#### 5.4.2, Turgor regulation in a closed system

In a closed system environment sugar beet taproot discs, freshly cut or pre-treated in a concentrated sucrose and/or KCl osmoticum, undergo upward turgor regulation to a single set point (between 0.6 and 0.7 MPa) within 40 - 80 minutes (this chapter). This turgor pressure ( $P_{cell}$ ) level corresponds to  $P_{cell}$  maintained by the 300 mM mannitol open



system beet discs (this chapter), and also corresponds to  $P_{\text{cell}}$  in intact, mature taproots *in vivo* (Tomos *et al.*, 1992). The time taken to achieve turgor regulation is dependent on the concentration of the pre-treatment osmoticum and the presence or absence of KCl.

Freshly cut, unrinsed beet discs have an initial  $P_{\text{cell}}$  value which is lower than  $P_{\text{cell}}$  *in vivo* (Tomos *et al.*, 1992). Beet disc preparation inevitably damages the tissue; cells rupture and release their contents into the apoplast leading to a decrease in  $P_{\text{cell}}$ . Pre-treating beet discs in 600 mOsmoles  $\text{kg}^{-1}$  sucrose and/or KCl has a comparable effect on  $P_{\text{cell}}$  (this chapter). Turgor regulation in freshly cut and 600 mOsmoles  $\text{kg}^{-1}$  sucrose and/or KCl pre-treated discs largely follows the same pattern. Following a lag of approximately 20 minutes,  $P_{\text{cell}}$  was regulated upwards, reaching 0.6 MPa - 0.7 MPa within 40 minutes. The exception being beet discs pre-treated in an osmoticum which was completely devoid of KCl. In the absence of apoplastic KCl turgor regulation was achieved within 60 minutes, after a lag of up to 30 minutes. Due to the larger osmotic pressure step/difference across the plasma membrane in beet discs pre-treated in 900 mOsmoles  $\text{kg}^{-1}$  sucrose and/or KCl, turgor regulation took 60 minutes in discs with apoplastic KCl and 80 minutes in discs without apoplastic KCl, after a lag of 20 and 40 minutes respectively. Providing the overall osmolarity of the sucrose and/or KCl pre-treatment was the same - micromolar (0.5 mM/500 $\mu$ M) and millimolar (300 - 900 mOsmoles  $\text{kg}^{-1}$ ) apoplastic KCl resulted in an indistinguishable turgor regulation pattern (this chapter). Changes in turgor pressure ( $P_{\text{cell}}$ ) were not accompanied by equivalent changes in cell osmotic pressure ( $\Pi_{\text{cell}}$ ), indicating that osmotic adjustment leading to turgor regulation is apoplastic rather than protoplasmic (this chapter).

The observed lag period, prior to the initiation of turgor regulation in closed system beet discs, may simply be an undesirable effect of beet disc preparation. The act of obtaining a core of beet tissue, followed by slicing the discs may produce a wounding response which affects the membrane transport processes necessary to achieve osmotic adjustment. For example, the plant plasma membrane proton ATPase (proton pump) acts as a primary transporter by pumping protons out of the cell, thereby creating pH and electrical potential differences across the plasma membrane. Transport of many solutes into and out of the cell involves secondary transporters whose ability to function



is directly dependent on the proton motive force created by the proton ATPase (for reviews see Serrano, 1989 and 1990; Michelet and Boutry, 1995). Inhibition of plasma membrane proton ATPase activity has been observed after mechanical shock to plant tissues (Hanson and Trewavas, 1982); mechanical shock includes cutting and slicing. The pH and solute content of the pre-treatment osmotica must also be considered as potential membrane transport inhibitors. The pre-treatment procedure almost certainly abolishes the acid-exterior pH gradient generated by the proton pump. The osmotica used all had a pH which was close to neutrality (data not shown), whereas the apoplast *in vivo* is generally acidic (Tetlow and Farrar, 1993; Husted and Schjoerring, 1995; Felle, 1998). The presence or absence of particular apoplastic solutes may also inhibit membrane transport. Apoplastic potassium ( $K^+$ ) stimulates plasma membrane ATPase activity (Briskin, 1990; Briskin and Hanson, 1992). Evidence pointing to an inhibition of membrane transport due to the absence of apoplastic  $K^+$  is presented in this chapter. As I highlighted above, beet discs pre-treated in an osmoticum which is devoid of KCl, achieved complete turgor regulation (to the target  $P_{cell}$  level of 0.6 MPa - 0.7 MPa) within 60 - 80 minutes (depending on the concentration of the sucrose pre-treatment osmoticum); 20 minutes longer than turgor regulation in the presence of apoplastic KCl (this chapter).

Potassium is a major nutrient in higher plants, where it plays a crucial role in turgor maintenance, charge balance and protein synthesis (Leigh and Wyn Jones, 1984). Addition of  $K^+$ , at micromolar concentrations, to  $K^+$  starved barley and maize roots elicits membrane depolarisation and net  $H^+$  efflux (Behl and Raschke, 1987; Kochian *et al.*, 1989). This net increase in  $H^+$  efflux is due to stimulation of the plasma membrane proton ATPase (Briskin, 1990; Briskin and Hansen, 1992; Briskin and Gawienowski, 1996). From early work on this enzyme, it was suggested that stimulation of activity by  $K^+$  might reflect the direct transport of this cation by the proton ATPase (Leonard, 1982 and references therein). Subsequent investigations, however, have revealed that this is not the case. Stimulation of the enzyme activity of a primary transporter by a cation is not always indicative of a direct role in the transport of that cation. For example, the ATPase activity of the animal sarcoplasmic reticulum  $Ca^{2+}$ -ATPase is stimulated by monovalent cations, including  $K^+$ , this clearly does not reflect direct  $K^+$  transport by this enzyme (see Tonomura, 1986). However,  $K^+$  stimulation of the sarcoplasmic reticulum



$\text{Ca}^{2+}$ -ATPase is also accompanied by an increase in phosphoenzyme turnover in the enzyme reaction mechanism, suggesting that  $\text{K}^+$  acts as an effector or modulator of ATPase activity (Tonomura, 1986 and references therein). Briskin and Gawienowski (1996) propose that this may also point to the mode of proton ATPase stimulation, by  $\text{K}^+$ , in higher plants.

The proton ATPase may not facilitate  $\text{K}^+$  uptake into the cell directly, however, the proton motive force generated by the proton ATPase is essential in driving the secondary transport of  $\text{K}^+$  into the cell (Briskin and Gawienowski, 1996; Maathuis and Sanders, 1996 and 1997). Two pathways for  $\text{K}^+$  uptake across the plasma membrane have been identified - the high affinity  $\text{K}^+$  pathway (Maathuis and Sanders, 1996 and 1997; Maathuis *et al.*, 1997) and the low affinity  $\text{K}^+$  pathway (Maathuis and Sanders, 1996 and 1997). High affinity  $\text{K}^+$  uptake from micromolar external  $\text{K}^+$  levels is coupled to  $\text{H}^+$  transport in a 1 : 1  $\text{H}^+/\text{K}^+$  symport. Low affinity  $\text{K}^+$  uptake, induced at relatively high external  $\text{K}^+$  levels in the millimolar range, is achieved by passive  $\text{K}^+$  transport (down an electrochemical  $\text{K}^+$  gradient) via a plasma membrane inwardly rectifying  $\text{K}^+$  channel ( $\text{K}^+$  IRC channel). A  $\text{H}^+/\text{K}^+$  symporter and an IRC channel are illustrated in **Chapter 6, Figure 6.3**.

From the sucrose and/or KCl upward turgor regulation data presented in this chapter, it would appear that both sucrose and KCl are utilised for osmotic adjustment purposes in sugar beet taproot tissue. Wyse *et al.* (1986) presented data which demonstrated that a decrease in turgor pressure ( $P_{\text{cell}}$ ) in sugar beet taproot discs, induced by an increase in external mannitol concentration, leads to an increase in sucrose uptake into the cell, driven by turgor dependent modulation of plasma membrane proton ATPase activity (the turgor dependent nature of the proton ATPase is demonstrated and discussed in **Chapter 6**). The turgor dependent regulation of sucrose transport in beet tissue is described in greater detail in the concluding discussion (**Chapter 7**).

Turning to the role of apoplastic  $\text{K}^+$  in turgor regulation. Turgor pressure ( $P_{\text{cell}}$ ) in red beet taproot tissue (also *Beta vulgaris* L.) is maintained at 0.5 MPa throughout the growing season (Perry *et al.*, 1987), whereas the osmotic pressure ( $\Pi_{\text{cell}}$ ) reaches



approximately 1.0 MPa as the taproot reaches maturity (Perry *et al.*, 1987). Efflux analysis of solutes present in the cell wall of red beet taproot tissue has revealed that free apoplastic  $K^+$  is present at concentrations sufficient to account for the difference between  $P_{cell}$  and  $\Pi_{cell}$  in this tissue (Leigh and Tomos, 1983). Furthermore, Bell and Leigh (1996) showed that turgor dependent  $K^+$  transport in sugar beet taproot tissue modulates the  $K^+$  concentration of the apoplast, thus facilitating turgor regulation. For example, an increase in turgor pressure, induced by decreasing the external mannitol concentration, leads to the initial loss of sucrose and  $K^+$  out of the cell. Sucrose is selectively retrieved from the apoplast, whereas the  $K^+$  is not. This leads to an accumulation of  $K^+$  in the adjacent apoplast. This in turn, increases the osmotic pressure of the apoplast ( $\Pi_{wall}$ ), resulting in a decrease in turgor pressure ( $P_{cell}$ ) and turgor regulation (Bell and Leigh, 1996). The work carried out by Bell and Leigh (1996) is described further in Chapter 7. All the available evidence suggests that beet taproot tissue, *in vivo*, utilises  $K^+$ , rather than sucrose, for apoplastic osmotic adjustment purposes (Leigh and Tomos, 1983; Tomos *et al.*, 1992; Bell and Leigh, 1996).

Sugar beet disc pre-treatment in a highly dilute osmoticum, such as 0 mM mannitol-0.5 mM  $CaSO_4$ , leads to a large increase in turgor pressure ( $P_{cell}$ ), due to water influx. Under closed system conditions this increase in  $P_{cell}$  does not initiate a downward turgor regulation mechanism; turgor pressure is maintained between 1.0 MPa and 1.2 MPa for the duration of the 90 minute time course (this chapter). However, I am inclined to be suspicious of these data. Wyse *et al.* (1986) and Bell and Leigh (1996) have clearly demonstrated that an increase in beet taproot turgor pressure ( $P_{cell}$ ) induces solute efflux. In theory, solute efflux, under closed system conditions, should lead to the accumulation of solutes in the apoplast and a decrease in  $P_{cell}$ . It could be argued that failure to achieve downward turgor regulation, in closed system beet tissue (this chapter), casts some doubt on the apoplastic solute adjustment hypothesis. However, the upward turgor regulation data (this chapter) is far too compelling to ignore. As I highlighted in Chapter 4, an apparent upward turgor regulation mechanism in closed system plant tissue, may be due to water uptake from the apoplast. However, this scenario cannot account for the fact that turgor pressure ( $P_{cell}$ ) is regulated upward to a single set point, which corresponds to  $P_{cell}$  in intact taproots *in vivo*. Furthermore, a



turgor pressure increase facilitated by apoplastic water uptake cannot account for the observed optimisation of turgor regulation in the presence of KCl.

I propose that the magnitude of the osmotic pressure step across the plasma membrane, leading to a rapid and large increase in cell turgor pressure, may inhibit membrane transport. Wyse *et al.* (1986) demonstrated that proton efflux, due to plasma membrane proton ATPase activity, is sharply reduced at high turgor pressures (see also Chapter 6). Inhibition of this major primary transporter is likely to inhibit the subsequent secondary transport of solutes necessary to achieve osmotic adjustment. In hindsight less extreme pre-treatment osmotica (100 - 200 mOsmoles kg<sup>-1</sup> sucrose and/or KCl) should also have been used to determine whether downward regulation of  $P_{\text{cell}}$  is achieved in beet tissue under closed system conditions.



## 5.5, Summary and conclusions

- Turgor pressure ( $P_{\text{cell}}$ ) in open system sugar beet taproot discs, aerated in mannitol osmotica of varying concentration, is initially determined by the osmotic pressure step across the plasma membrane.
- Over 48 hours  $P_{\text{cell}}$  is regulated upward and downward (depending on the concentration of the mannitol osmoticum) towards the  $P_{\text{cell}}$  level found in intact (physiologically comparable) taproots *in vivo* (0.6 - 0.7 MPa - Tomos *et al.*, 1992).
- Changes in  $P_{\text{cell}}$  are accompanied by corresponding changes in cell osmotic pressure ( $\Pi_{\text{cell}}$ ), indicating that osmotic adjustment, leading to turgor regulation, is protoplasmic in nature in this case.
- Under closed system conditions an increase in apoplastic solute concentration, brought about by the rupture of adjacent cells or by pre-treatment in an osmoticum, leads to an initial decrease in  $P_{\text{cell}}$ .
- This decrease in  $P_{\text{cell}}$  initiates a turgor regulation mechanism which is strongly dependent on the permeant properties of the apoplastic solutes.
- In freshly cut beet discs and beet discs pre-treated in sucrose and/or KCl osmotica, upward turgor regulation is achieved within 40 - 80 minutes. Turgor ( $P_{\text{cell}}$ ) is regulated to a single set point (about 0.65 MPa) which corresponds to  $P_{\text{cell}}$  in intact (physiologically comparable) taproots *in vivo*.
- Turgor regulation in the presence of apoplastic KCl is achieved 20 minutes sooner than turgor regulation in the absence of apoplastic KCl, suggesting that apoplastic KCl facilitates membrane transport.



- ❑ Turgor regulation in a closed system is not accompanied by corresponding changes in  $\Pi_{\text{cell}}$ . This indicates that osmotic adjustment of solutes, necessary to achieve turgor regulation, is apoplastic rather than protoplasmic in nature.
  
- ❑ An increase in  $P_{\text{cell}}$ , induced by beet disc pre-treatment in a highly dilute osmoticum does not initiate downward turgor regulation. This may be due to membrane transport inhibition induced by the magnitude of the osmotic pressure step across the plasma membrane.
  
- ❑ The upward turgor regulation mechanism in closed system sugar beet discs is comparable to the closed system turgor regulation mechanism observed in *Suaeda maritima* leaf epidermal cells (Chapter 4).



## **Chapter 6 : The turgor dependent nature of the plasma membrane proton ATPase in *Beta vulgaris* L. (sugar beet) taproot tissue**

### **6.1, Introduction**

The osmotic adjustment mechanisms described in Chapter 3 through to Chapter 5 are largely achieved by the stimulation and modulation of membrane transport processes. In plants, solute transport across the plasma membrane is driven by the electrochemical and pH gradients generated by the plasma membrane proton ATPase (Slayman, 1974; Poole, 1978; Spanswick, 1981; Sze, 1985; Serrano, 1989 and 1990; Michelet and Boutry, 1995). For, example, the secondary transporters which facilitate the transport of cations, anions (Michelet and Boutry, 1995), amino acids (Reinhold and Kaplan, 1984), sugars (Giaquinta, 1983), and growth regulators (Goldsmith, 1977) are (with few exceptions) dependent on plasma membrane proton ATPase activity (a primary transporter). Figure 6.1, 6.2 and 6.3 illustrate the secondary transport of Na<sup>+</sup>, sucrose and K<sup>+</sup> respectively.

#### **6.1.1, The plasma membrane proton ATPase**

Proton ATPases are the main electrogenic pumps in higher plants (Sze, 1985). The structure and mechanism of these enzymes are similar to that of other ATPases including the Na<sup>+</sup>/K<sup>+</sup> ATPase (sodium pump) of animal cells, the gastric H<sup>+</sup>/K<sup>+</sup> ATPase, and the Ca<sup>2+</sup> ATPase of the sarcoplasmic reticulum (Serrano, 1989). These enzymes are collectively referred to as P-type ATPases because they form a phosphorylated intermediate during their reaction cycle (Serrano, 1989 and 1990).

The plant plasma membrane ATPase, a protein with a molecular mass of about 100 kD, is composed of a single polypeptide that is predicted to be anchored in the plasma membrane by 10 membrane spanning regions (Wach *et al.*, 1992). It transports one proton per molecule of ATP hydrolysed, has a pH optimum of 6.6, and is inhibited by vanadate, dicyclohexylcarbodiimide, diethylstilbestrol, and erythrosin B (Michelet and



Boutry, 1995). Described as the “Master Enzyme” by Serrano in 1989, the plasma membrane proton ATPase plays a central role in plant physiology, controlling many important cellular functions, including: energisation of secondary solute transport, regulation of turgor pressure, cell wall extension, and intracellular pH regulation (Michelet and Boutry, 1995).

### 6.1.2, Modulation of plasma membrane proton ATPase activity

Plant plasma membrane proton ATPase activity can be modulated by a diverse range of stimuli. Light stimulates proton ATPase activity in guard cells, this drives K<sup>+</sup> influx, which in turn leads to an increase in guard cell turgor pressure and opening of the stomatal aperture (Assmann *et al.*, 1985; Shimazaki *et al.*, 1986; Serrano *et al.*, 1988). Plant growth regulators also interact with the proton ATPase. Auxin activates the enzyme in the growing regions of shoots, promoting cell elongation (Brummell and Hall, 1987; Rayle and Cleland, 1992). Abscisic acid, however, inhibits plasma membrane proton ATPase activity in a number of plant tissues, for example, proton ATPase inhibition by abscisic acid induces stomatal closure, prevents seed germination, and inhibits xylem loading in roots (Serrano, 1989 and references therein). Fusicoccin is a phytotoxin produced by the fungus *Fusicoccum amygdali* (Ballio *et al.*, 1964). In many ways fusicoccin mimics the plant growth regulator auxin in that it stimulates plasma membrane proton ATPase activity and hence proton efflux (Lanfermeijer and Prins, 1994; Jahn *et al.*, 1996; De Michelis *et al.*, 1996; De Boer, 1997; this chapter). Due to its growth regulator like mode of action, fusicoccin has been widely studied by plant physiologists (Marré, 1979). More recently, however, interest in fusicoccin has shifted to its receptor site on the plasma membrane and the role of this receptor in signal transduction (Aducci *et al.*, 1995; Ferl, 1996; Jahn *et al.*, 1997).

The plasma membrane proton ATPase modulators with the most relevance to the work described in this study (Chapter 3 through to 5) are NaCl and turgor pressure. In halophytes, NaCl stimulates proton ATPase activity (Ayala *et al.*, 1996; Wu and Seliskar, 1998). Ayala *et al.* (1996) found that *Salicornia bigelovii* plants grown in 200 mM NaCl had a 60 % higher plasma membrane proton ATPase activity than equivalent plants grown in the absence of NaCl. Wu and Seliskar (1998) reported similar findings



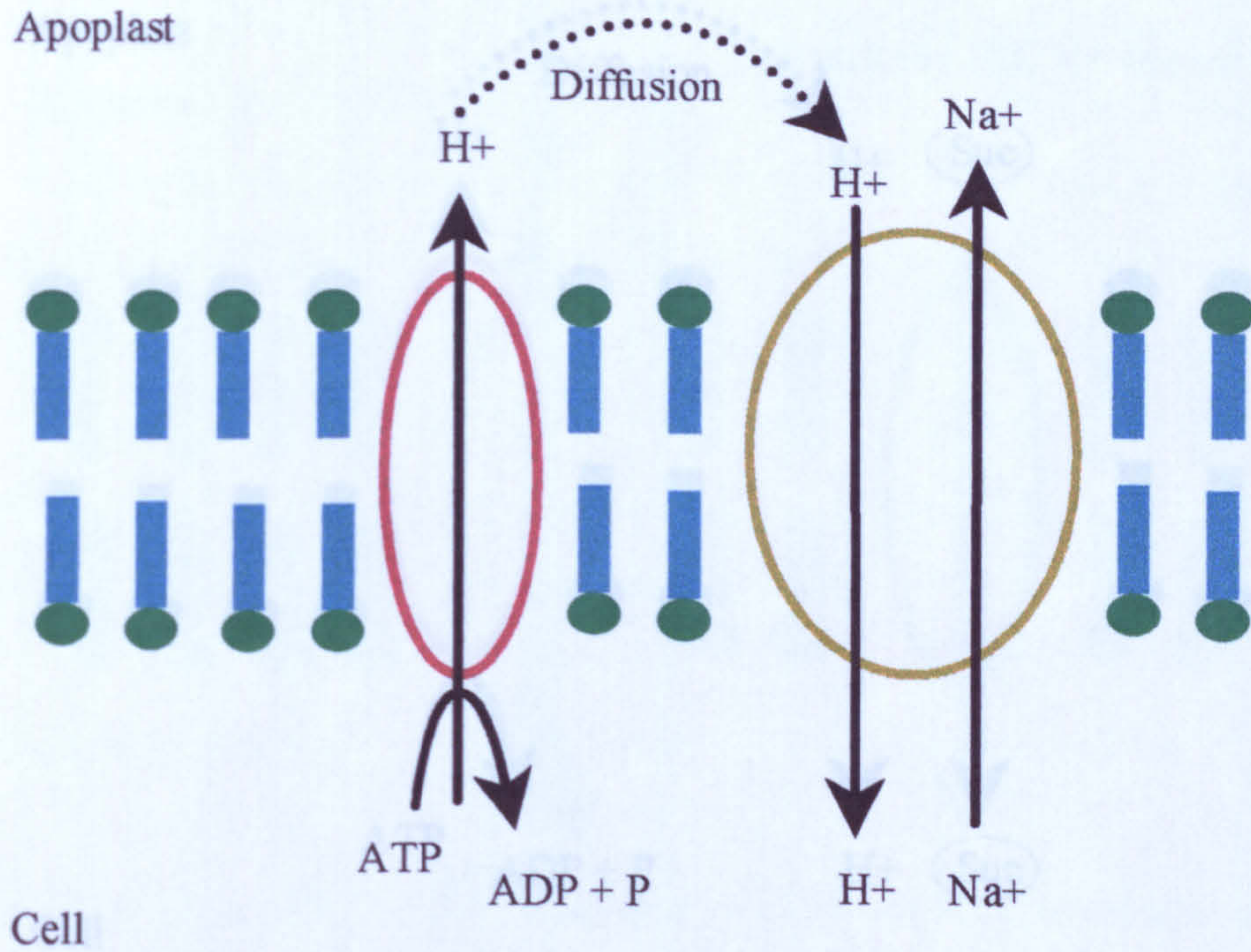
in the C<sub>4</sub> plant *Spartina patens*. Callus cultures of *Spartina patens* grown on 340 mM NaCl had a plasma membrane proton ATPase activity which was 250 % greater than in calli cultured in the absence of NaCl. Furthermore, studies on *Atriplex nummularia* have revealed that optimum plasma membrane proton ATPase activity is only achieved in the presence of NaCl in this species (Braun *et al.*, 1986).

Turning to the affect of turgor pressure ( $P_{\text{cell}}$ ) on plasma membrane proton ATPase activity. A decrease in cell turgor pressure, induced by an increase in the concentration of the external medium, stimulates proton ATPase activity leading to an increase in proton efflux and a greater transmembrane potential difference. This turgor induced phenomenon has been observed in a number of plant tissues, including: *Arabidopsis thaliana* cell cultures (Curti *et al.*, 1993; Teodoro *et al.*, 1998), broad bean mesocarp cells ( Ze-Sheng and Delrot, 1987), pea internode segments (Marré *et al.*, 1973; Cleland, 1975), oat coleoptiles (Cleland, 1975), *Senecio mikanioides* leaf segments (Reinhold *et al.*, 1984), carrot cell cultures (Reuveni *et al.*, 1987) and sugar and red beet taproot tissue (Kinraide and Wyse, 1986; Wyse *et al.*, 1986; Tomos, 1989; this chapter). It has been suggested that this mechanism plays an essential role in turgor regulation (Giaquinta, 1983; Reinhold *et al.*, 1984; Ze-Sheng and Delrot, 1987). In this chapter, the turgor dependent nature of proton efflux in sugar beet taproot tissue is investigated using a delightfully simple method. The turgor pressure ( $P_{\text{cell}}$ ) of sugar beet taproot discs is modulated using mannitol osmotica of varying concentration. Proton efflux is determined by titration with potassium hydroxide (KOH), while the molecular basis of the proton efflux mechanism is determined using inhibitors and activators of membrane transport.



**Figure 6.1, Sodium efflux**

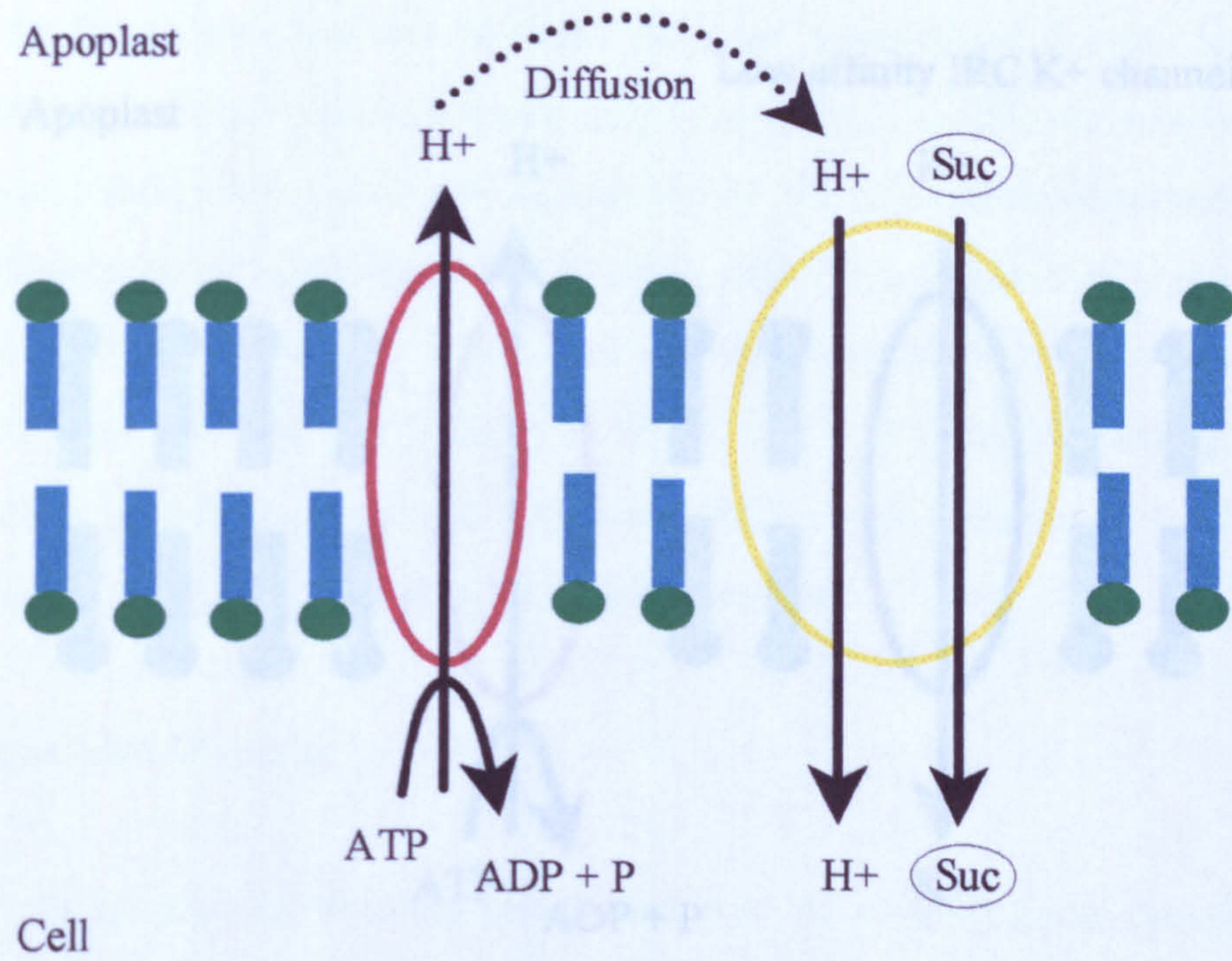
Sodium efflux, via a  $H^+/Na^+$  antiport system, driven by plasma membrane proton ATPase activity (see Rausch *et al.*, 1996).





**Figure 6.2, Sucrose influx**

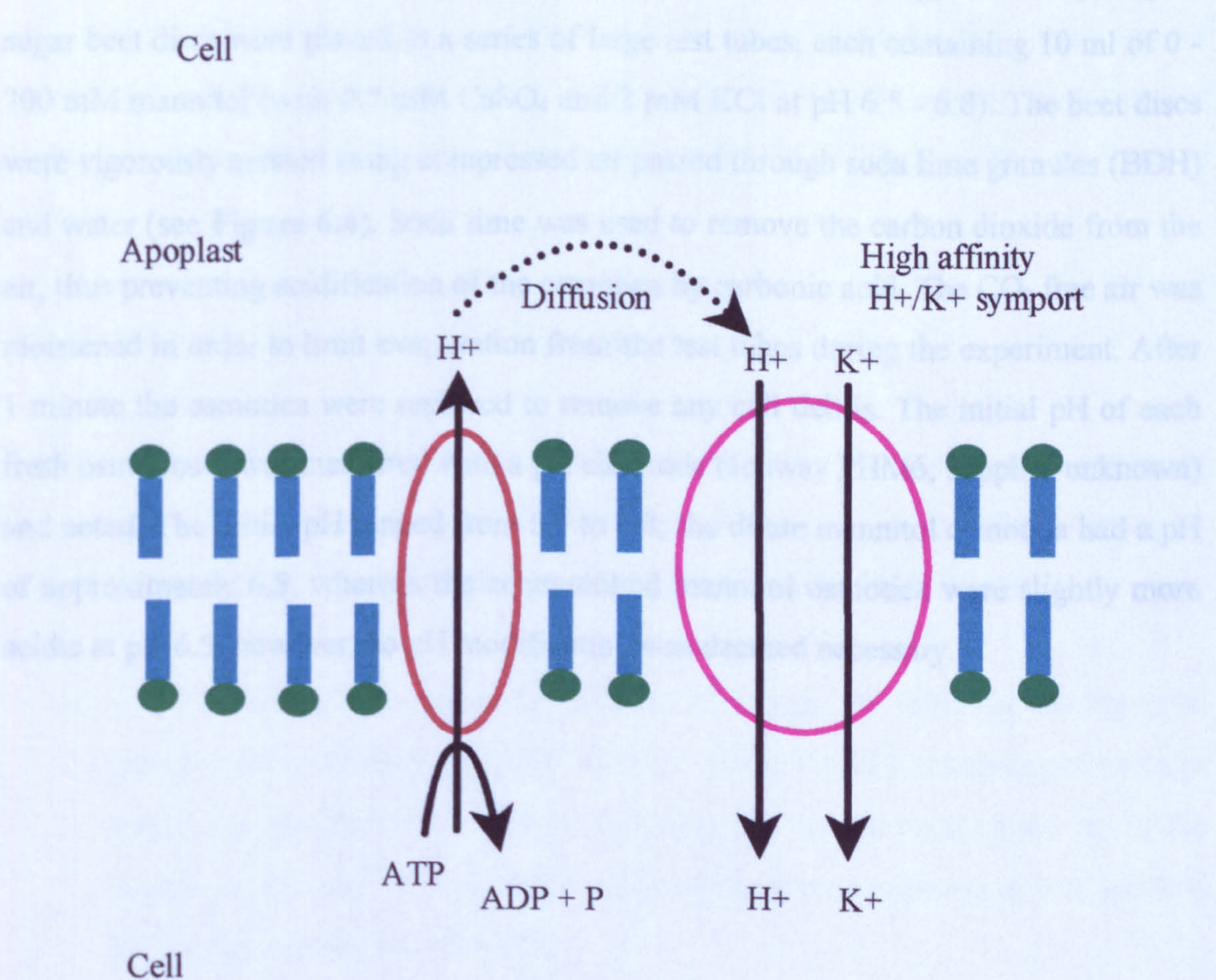
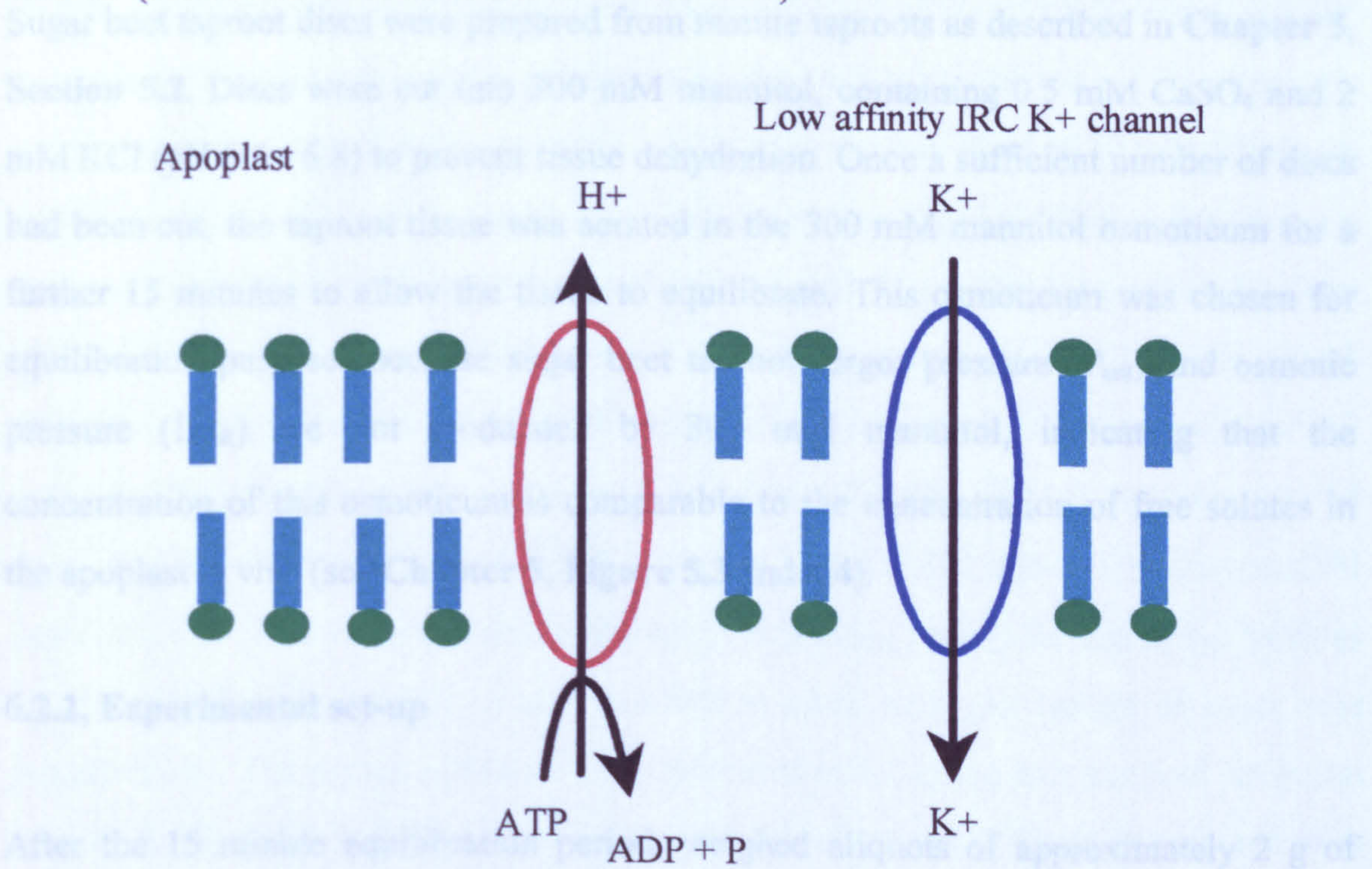
Sucrose uptake into the cell via a  $H^+$ / sucrose symport system, driven by plasma membrane proton ATPase activity (see Giaquinta, 1983).





**Figure 6.3, Low affinity and high affinity  $K^+$  influx**

Low affinity  $K^+$  uptake, by diffusion down an electrochemical gradient, via an inwardly rectifying (IRC)  $K^+$  channel, and high affinity  $K^+$  uptake achieved by a 1 : 1 symport with  $H^+$  (see Maathuis and Sanders 1996 and 1997).





## 6.2, Method

### 6.2.1, Sugar beet disc preparation

Sugar beet taproot discs were prepared from mature taproots as described in Chapter 5, Section 5.2. Discs were cut into 300 mM mannitol, containing 0.5 mM CaSO<sub>4</sub> and 2 mM KCl (pH 6.5 - 6.8) to prevent tissue dehydration. Once a sufficient number of discs had been cut, the taproot tissue was aerated in the 300 mM mannitol osmoticum for a further 15 minutes to allow the tissue to equilibrate. This osmoticum was chosen for equilibration purposes because sugar beet taproot turgor pressure ( $P_{\text{cell}}$ ) and osmotic pressure ( $\Pi_{\text{cell}}$ ) are not modulated by 300 mM mannitol, indicating that the concentration of this osmoticum is comparable to the concentration of free solutes in the apoplast *in vivo* (see Chapter 5, Figure 5.3 and 5.4).

### 6.2.2, Experimental set-up

After the 15 minute equilibration period, weighed aliquots of approximately 2 g of sugar beet discs were placed in a series of large test tubes, each containing 10 ml of 0 - 700 mM mannitol (with 0.5 mM CaSO<sub>4</sub> and 2 mM KCl at pH 6.5 - 6.8). The beet discs were vigorously aerated using compressed air passed through soda lime granules (BDH) and water (see Figure 6.4). Soda lime was used to remove the carbon dioxide from the air, thus preventing acidification of the osmotica by carbonic acid. The CO<sub>2</sub> free air was moistened in order to limit evaporation from the test tubes during the experiment. After 1 minute the osmotica were replaced to remove any cell debris. The initial pH of each fresh osmoticum was measured with a pH electrode (Jenway PHM6; supplier unknown) and noted. The initial pH ranged from 6.5 to 6.8; the dilute mannitol osmotica had a pH of approximately 6.8, whereas the concentrated mannitol osmotica were slightly more acidic at pH 6.5, however, no pH modification was deemed necessary.



### 6.2.3, Proton efflux determination

Proton efflux was determined by titration with potassium hydroxide (analytical grade; BDH). A pipette (Gilson; BDH) was used to expel 20  $\mu$ l of 10 mM KOH into each test tube. Using a stopwatch and the pH electrode, the time taken for the pH to return to a predetermined level (pH 6.6) was noted. At pH 6.6 a further 20  $\mu$ l of 10 mM KOH was added, and the procedure repeated - this continued for 4 hours. Figure 6.5 shows a chart recorder trace of change in osmoticum pH with time. The time taken for each KOH addition (of known volume and concentration) to be neutralised by the proton efflux mechanism was then used to calculate the rate of proton efflux in  $\text{nmol min}^{-1} / 2$  g tissue. The calculation was carried out as follows: 10 mM KOH is equivalent to 10  $\text{mmol l}^{-1}$ . Therefore in 20  $\mu$ l or 0.00002 l there is  $10 \times 0.00002$  mmol/0.0002 mmol/200 nmol of KOH. This value divided by the time (in minutes) taken for the added KOH to be neutralised gives the rate of proton efflux in  $\text{nmol min}^{-1}$  per weight of sugar beet taproot tissue. The proton efflux data are presented as the mean and standard deviation of individual KOH additions in a representative experiment. Each experiment was repeated at least 4 times (data not shown). The n number varies from treatment to treatment due to the differential nature of the proton efflux mechanism (the n number stated in each figure legend corresponds to the number of KOH titrations carried out in 4 hours).

### 6.2.4, Membrane transport inhibitors and activators

Inhibitors and activators of membrane transport were used to determine the nature of the proton efflux mechanism. Table 6.1 gives details of the membrane transport modulators used. Additional information is presented in bullet form below:

- **Anoxia** - sugar beet discs were starved of oxygen by bubbling the mannitol osmotica with nitrogen gas rather than air. The nitrogen gas was passed through soda lime granules and water in the same way as the compressed air in the control experiment. The recovery phase of the anoxia experiment was induced by simply restoring the air supply.



- **Potassium cyanide** - a 1 mM stock solution of potassium cyanide was carefully prepared under a fume hood. Due to the harmful nature of cyanide, the exact volume required was calculated to avoid any unnecessary excess. Potassium cyanide is strongly alkaline in aqueous solution. The mannitol osmotica made up with 1 mM KCN had an initial pH of between 10.5 and 10.8. The pH of the osmotica was adjusted with concentrated HCl (BDH) to between pH 6.5 - 6.8 prior to adding the sugar beet tissue. This procedure was carried out under supervision as acidifying KCN solution promotes the evolution of volatile HCN. Proton efflux determination, in the presence of cyanide, was carried out under a fume hood. Strict COSHH regulations were adhered to at all times.
  
- **p-Chloromercuriphenylsulphonic acid (PCMPS)** - a stock solution of 1 mM PCMPS was prepared and used to make up the mannitol-CaSO<sub>4</sub>-KCl osmotica as required.
  
- **Erythrosin B (EB)** - erythrosin B is relatively insoluble in water, but readily dissolves in an alkali. A 100 μM stock solution of EB was made up by diluting aliquots of potassium hydroxide, containing EB, in de-ionised water. The pH of the EB stock solution was modified to pH 6.5 - 6.8 as required, using HCl.
  
- **Verapamil** - verapamil is insoluble in water. A 100 μM stock solution was prepared by dissolving the verapamil in 1 ml of absolute ethanol before making up the solution with de-ionised water. An identical volume of ethanol was also added to the control osmotica.
  
- **Nifedipine** - nifedipine is also insoluble in water and is only sparingly soluble in ethanol. A 100 μM stock solution was prepared by dissolving the nifedipine in 1 ml of acetone (BDH) before making up the solution with de-ionised water. An identical volume of acetone was also added to the control osmotica.



- **Fusicoccin (FC)** - a 10  $\mu$ M stock solution was prepared in de-ionised water. The stock FC solution was then used to make up the 0 - 700 mM mannitol osmotica (with 0.5 CaSO<sub>4</sub> and 2 mM KCl).

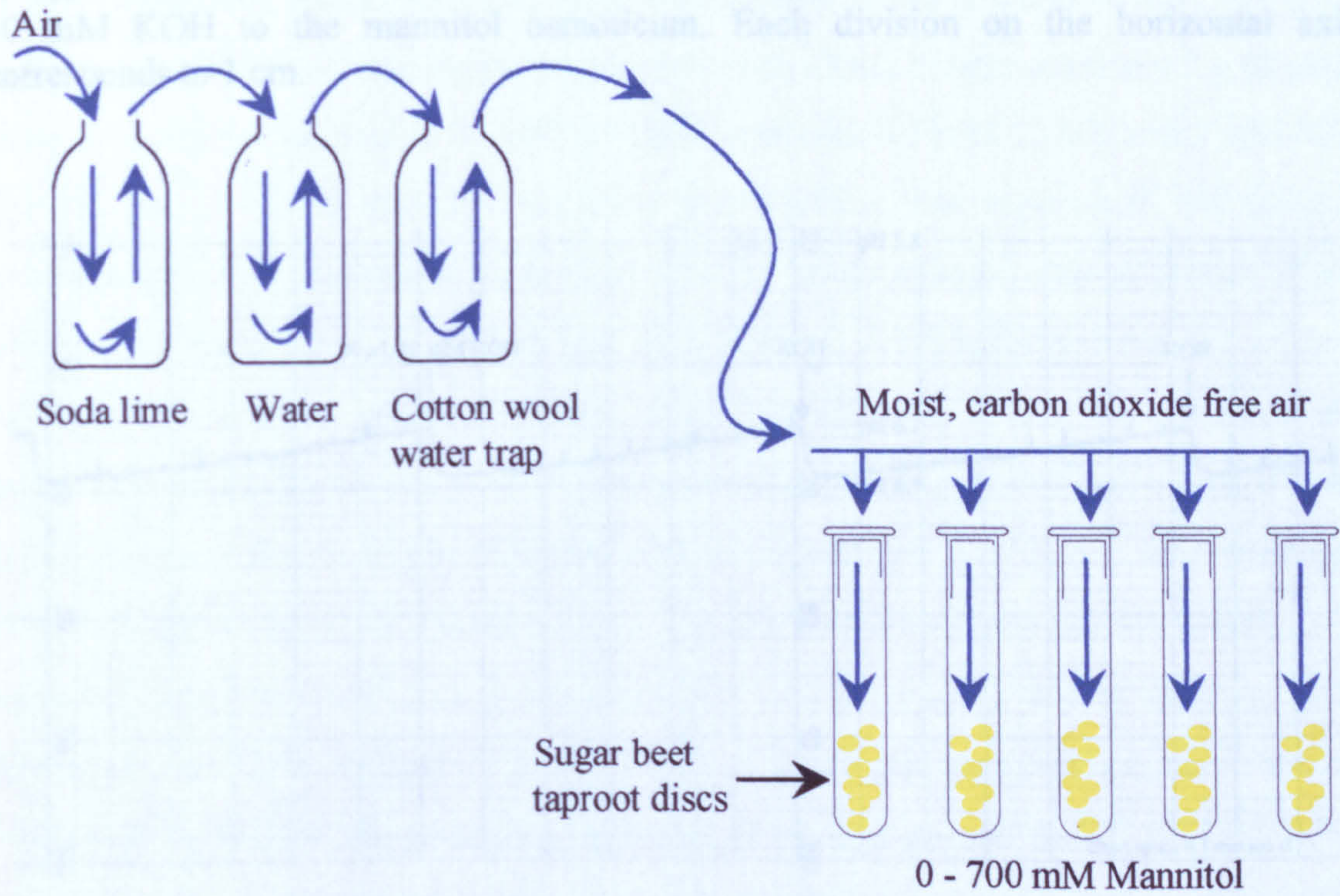
**Table 6.1, The membrane transport modulators used to determine the nature of the proton efflux mechanism in sugar beet taproot discs**

<b>Treatment</b>	<b>Concentration</b>	<b>Mode of action</b>	<b>Grade/Supplier</b>
<b>Nitrogen gas</b>	N/A	Respiratory chain inhibitor	BOC
<b>KCN</b>	1 mM	Respiratory chain inhibitor	Analytical grade / BDH
<b>PCMPS</b>	1 mM	Proton ATPase inhibitor	Analytical grade / Sigma
<b>EB</b>	100 $\mu$ M	Proton ATPase inhibitor	Analytical grade / Sigma
<b>Verapamil</b>	100 $\mu$ M	Calcium channel blocker	Analytical grade / Sigma
<b>Nifedipine</b>	100 $\mu$ M	Calcium channel blocker	Analytical grade / Sigma
<b>FC</b>	10 $\mu$ M	Proton ATPase activator	Analytical grade / Sigma



Figure 6.4, Experimental set-up

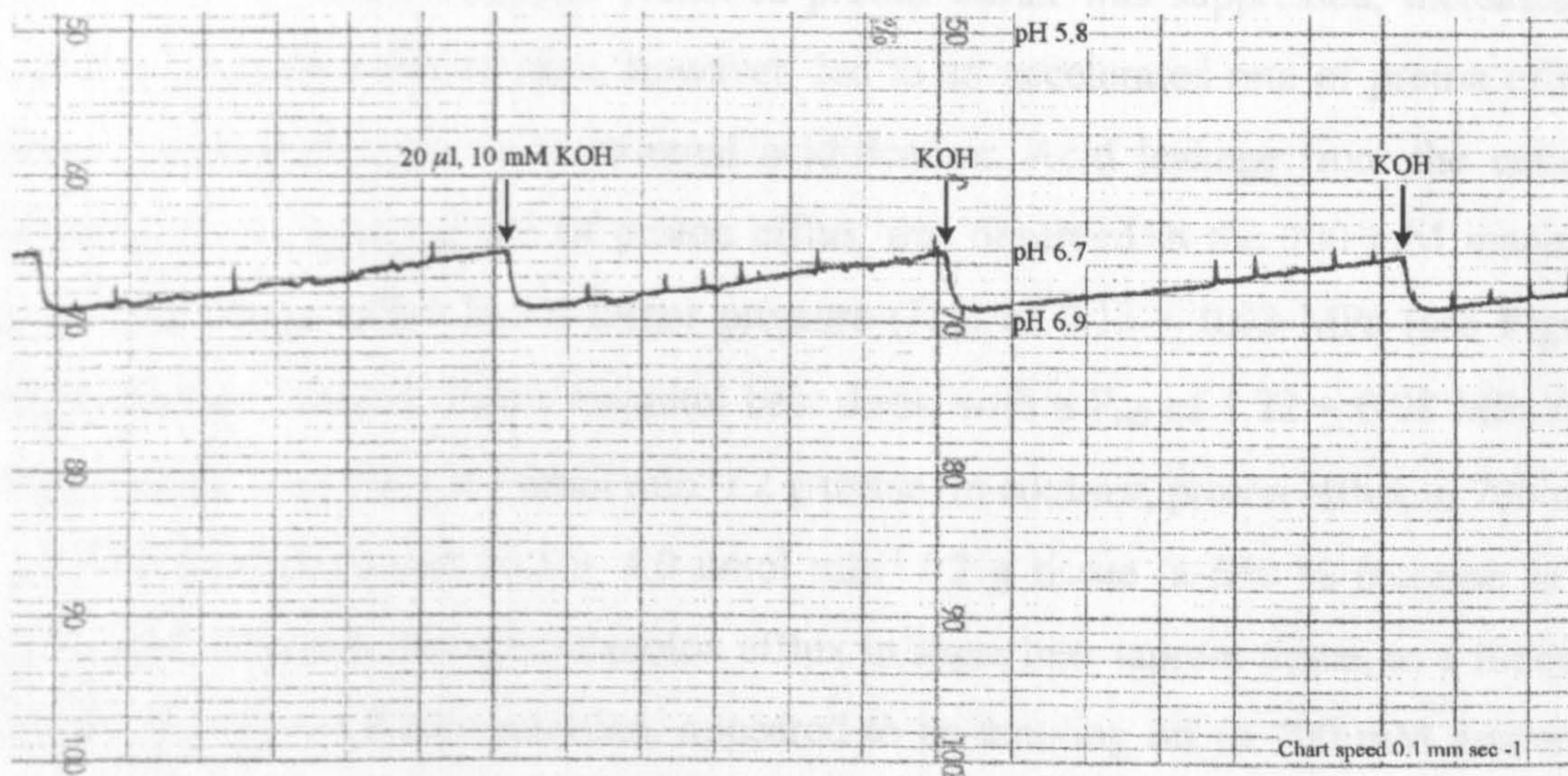
Acidification of 10 ml of 700 mM mannitol (containing 0.5 mM  $\text{CaSO}_4$  and 2 mM KCl) by approximately 2 g of sugar beet taproot tissue. Arrows indicate the addition of 20  $\mu\text{l}$ , 0.1 M KOH to the mannitol suspension. Each division on the horizontal axis corresponds to 10 min.





**Figure 6.5, Acidification of an external osmoticum by sugar beet taproot tissue**

Acidification of 10 ml of 700 mM mannitol (containing 0.5 mM  $\text{CaSO}_4$  and 2 mM KCl) by approximately 2 g of sugar beet taproot tissue. Arrows indicate the addition of 20  $\mu\text{l}$ , 10 mM KOH to the mannitol osmoticum. Each division on the horizontal axis corresponds to 1 cm.





### 6.3, Results

Turgor dependent proton efflux in sugar beet taproot tissue is demonstrated in Figure 6.6. Proton efflux was determined by titration with KOH, in approximately 2 g of sugar beet taproot discs, aerated in 0 - 700 mM mannitol with 0.5 mM CaSO<sub>4</sub> and 2 mM KCl, for 4 hours. In dilute mannitol osmotica proton efflux was suppressed, increases in external mannitol concentration, however, led to an accelerated rate of proton efflux, and a subsequent increase in external acidification. Acid leakage from the cells is unlikely, as the greatest rate of proton efflux was observed in the 700 mM mannitol sugar beet discs, which had a turgor pressure ( $P_{\text{cell}}$ ) of  $0.13 \pm 0.03$  MPa (see Figure 6.14). Proton efflux in 0 mM mannitol beet discs, with a  $P_{\text{cell}}$  of  $1.22 \pm 0.08$  MPa (see Figure 6.14), was  $3.5 \pm 0.2$  nmol min<sup>-1</sup> / 2 g tissue. In contrast, proton efflux in 700 mM mannitol beet discs was  $26.1 \pm 4.0$  nmol min<sup>-1</sup> / 2 g tissue (a 650 % increase in H<sup>+</sup> extrusion). However, the rate of proton efflux in sugar beet taproot tissue, as a function of external mannitol concentration, appeared to be tapering off in 700 mM mannitol, suggesting that proton efflux was approaching its optimal level at this point. These data demonstrate that sugar beet storage parenchyma cells respond to a turgor/osmotic related stimulus by modulating a membrane transport mechanism, leading to changes in proton efflux.

Inhibitors and activators of membrane transport were used to determine the nature of this proton efflux mechanism. Anoxia and KCN are crude membrane transport inhibitors in that they inhibit aerobic respiration and subsequently inhibit ATP production. Inhibition of proton efflux, in sugar beet taproot tissue, by anoxia and KCN would be consistent with this mechanism being an active process requiring oxygen and ATP. Figure 6.7 shows that anoxia suppressed proton efflux across the range of mannitol treatments. Proton efflux in 700 mM mannitol beet discs starved of oxygen was  $6.7 \pm 1.5$  nmol min<sup>-1</sup> / 2 g tissue, whereas in oxygen sufficient 700 mM mannitol discs proton efflux was  $25.8 \pm 4.1$  nmol min<sup>-1</sup> / 2 g tissue. The turgor dependent pattern of proton efflux was not completely abolished by the anoxia treatment. This may be due to the fact that the test tubes, in which the experiments were carried out, were completely open to ambient air. Inhibition by anoxia was found to be rapidly and



completely reversible. Proton efflux was restored to control values once the air supply was restored (Figure 6.7). Potassium cyanide (KCN) completely abolished proton efflux in all mannitol treatments (Figure 6.8).

Membrane transport inhibitors, more specific in nature, such as PCMPS and erythrosin B also inhibited proton efflux in sugar beet taproot tissue (Figure 6.9 and 6.10). PCMPS is a widely used sulfhydryl group inhibitor, which markedly inhibits sucrose uptake into excised sugar beet leaf and taproot tissue by inactivating the plasma membrane proton ATPase (Giaquinta, 1976 and 1983; Reinhold *et al.*, 1984; Wyse *et al.*, 1986). Figure 6.9 illustrates that proton efflux was largely inhibited by 1 mM PCMPS across the range of mannitol treatments. Proton efflux was not completely abolished in the 300 mM, 500 mM and 700 mM mannitol osmotica, but only reached  $1.0 \pm 0.02$  nmol min<sup>-1</sup> / 2 g tissue,  $1.3 \pm 0.05$  nmol min<sup>-1</sup> / 2 g tissue, and  $1.4 \pm 0.05$  nmol min<sup>-1</sup> / 2 g tissue respectively. Erythrosin B (EB) is an effective and highly specific plasma membrane proton ATPase inhibitor (Cocucci and Marré, 1986; Beffagna and Romani, 1988; Curti *et al.*, 1993; Walker *et al.*, 1995). As little as 100 mM EB completely abolished proton efflux in sugar beet taproot discs, in all treatments (Figure 6.10).

To summarise, sugar beet taproot storage parenchyma cells respond to a decrease in cell turgor pressure ( $P_{\text{cell}}$ ) or an increase in external osmotic pressure ( $\Pi_{\text{ext}}$ ) by increasing plasma membrane proton ATPase activity. However, the mechanism of stimulus detection, leading to the modulation of the proton ATPase remains unclear.

The role of calcium as a possible secondary messenger in the sequence of events leading to plasma membrane proton ATPase modulation was investigated using widely studied calcium channel blockers (for a review on calcium regulation and signalling in plants see Bush, 1995). There are currently two major groups of chemically distinctive calcium channel blockers, the phenylalkylamines, such as verapamil, methoxyverapamil, desmethoxyverapamil, diltiazem and bepridil, and 1,4-dihydropyridines, such as nifedipine and nitrendipine (Nayler and Horowitz, 1983; Miller and Freedman, 1984; Graziana *et al.*, 1988). Two calcium channel blockers (an



example from each group) were chosen to determine the effect of calcium flux inhibition on proton efflux in sugar beet taproot tissue. **Figure 6.11 and 6.12** illustrate that verapamil and nifedipine had no effect on proton efflux. The proton efflux pattern in calcium channel blocker treated beet discs was indistinguishable from that in control sugar beet discs. However, no positive control was carried out to determine whether the calcium channel blockers were effective. Therefore, I cautiously conclude that  $\text{Ca}^{2+}$  is not involved in the turgor/osmotic sensing mechanism, leading to plasma membrane proton ATPase modulation in this case.

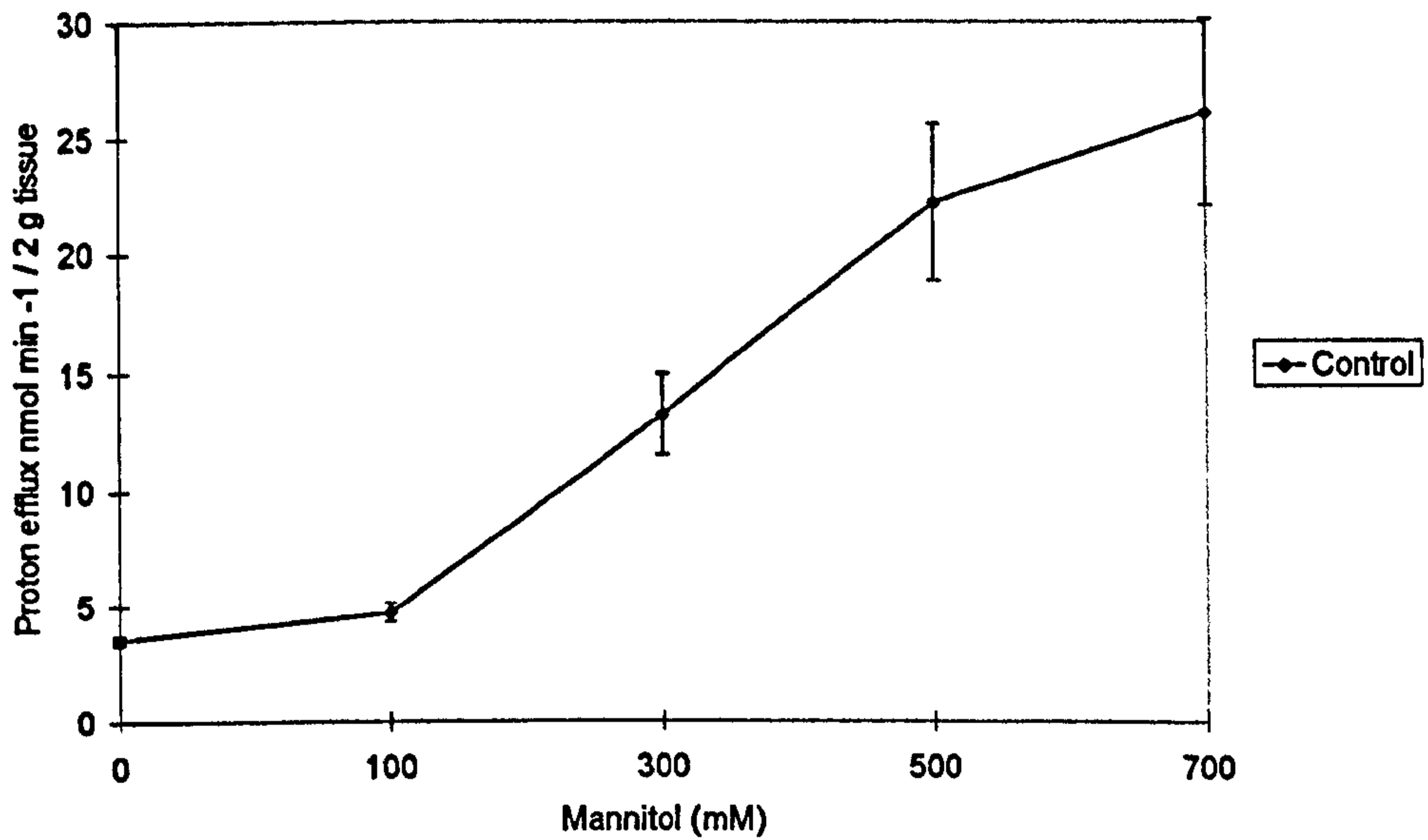
Fusicoccin (FC) is a phytotoxin which strongly stimulates proton efflux in plant tissue (Rayle, 1973; Senn and Goldsmith, 1988; Lüthen *et al.*, 1990; this chapter, Figure 6.13). This increase in  $\text{H}^+$  extrusion in the presence of fusicoccin is due to plasma membrane proton ATPase stimulation (Johansson *et al.*, 1993; Rasi-Caldogno *et al.*, 1993; Lanfermeijer and Prins, 1994; Jahn *et al.*, 1996). This stimulation of proton efflux by fusicoccin is demonstrated in **Figure 6.13**. The presence of  $10 \mu\text{M}$  FC increased proton efflux, in sugar beet taproot discs, to around  $40 \text{ nmol min}^{-1} / 2 \text{ g tissue}$  throughout the range of mannitol treatments. The differential response to turgor pressure ( $P_{\text{cell}}$ ) or external osmotic pressure ( $\Pi_{\text{ext}}$ ) was apparently abolished. These data suggest that the site of turgor/osmotic responsiveness, in sugar beet storage parenchyma cells, is the same as or “up stream” from that of fusicoccin sensitivity.

**Figure 6.14** demonstrates the modulation of sugar beet taproot cell turgor pressure by external mannitol osmotica of varying concentration. Turgor pressure in sugar beet discs aerated in 0 mM, 100 mM, 300 mM, 500 mM and 700 mM mannitol (each containing 0.5 mM  $\text{CaSO}_4$  and 2 mM KCl), for 4 hours, were  $1.22 \pm 0.08 \text{ MPa}$ ,  $0.97 \pm 0.08 \text{ MPa}$ ,  $0.65 \pm 0.1 \text{ MPa}$ ,  $0.39 \pm 0.05 \text{ MPa}$  and  $0.13 \pm 0.03 \text{ MPa}$  respectively. Turgor pressure was measured using the cell pressure probe (see **Chapter 2, Section 2.2**). The data are presented as mean and standard deviation, n is 15 (5 beet discs, 3 cells per disc).



**Figure 6.6, Turgor/osmotic dependent proton efflux in sugar beet taproot discs**

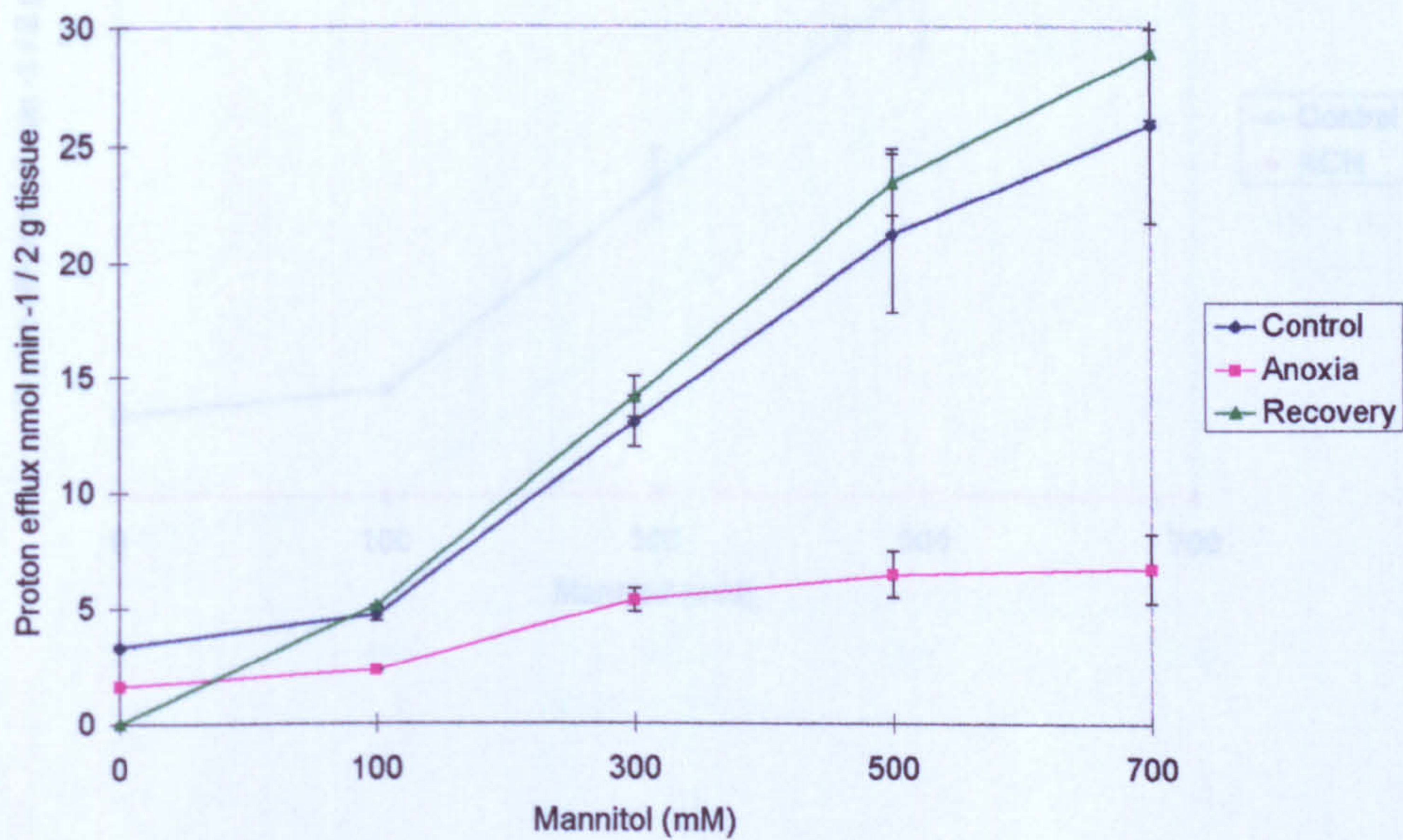
Mean proton efflux in approximately 2 g of sugar beet taproot tissue aerated in 10 ml of 0 - 700 mM mannitol, with 0.5 mM CaSO<sub>4</sub> and 2 mM KCl, over 4 hours. Data are presented as mean and standard deviation of individual KOH additions, n is 5, 15, 25 and 30 in the 0 - 100 mM, 300 mM, 500 mM and 700 mM mannitol osmotica respectively.





**Figure 6.7, Reversible inhibition of proton efflux by anoxia**

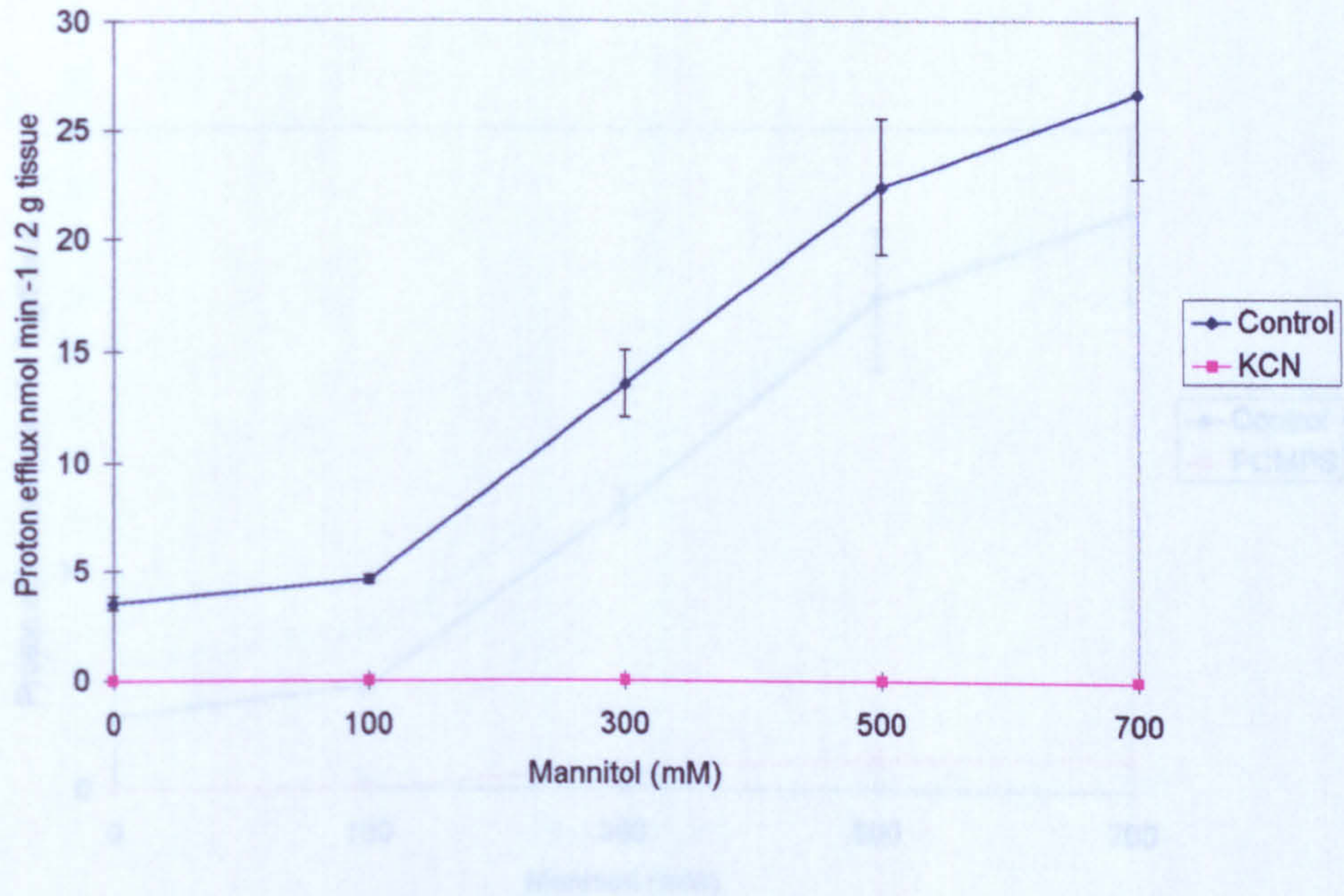
Mean proton efflux in sugar beet taproot tissue in 10 ml of 0 - 700 mM mannitol, containing 0.5 mM  $\text{CaSO}_4$  and 2 mM KCl, with sufficient or in the absence of oxygen, over 4 - 8 hours. Data are presented as mean and standard deviation of individual KOH additions, n is 10, 30, 50 and 60 in control 0 - 100 mM, 300 mM, 500 mM and 700 mM mannitol osmotica respectively (over 8 hours). In the anoxia treated discs n is 2 and 5 in 0 -100 mM and 300 - 700 mM mannitol osmotica respectively (over the first 4 hours). In the recovery beet discs n is 1, 5, 15, 25, and 30 in 0 mM, 100 mM, 300 mM, 500 mM and 700 mM mannitol osmotica respectively (over the last 4 hours).





**Figure 6.8, Complete inhibition of proton efflux by potassium cyanide**

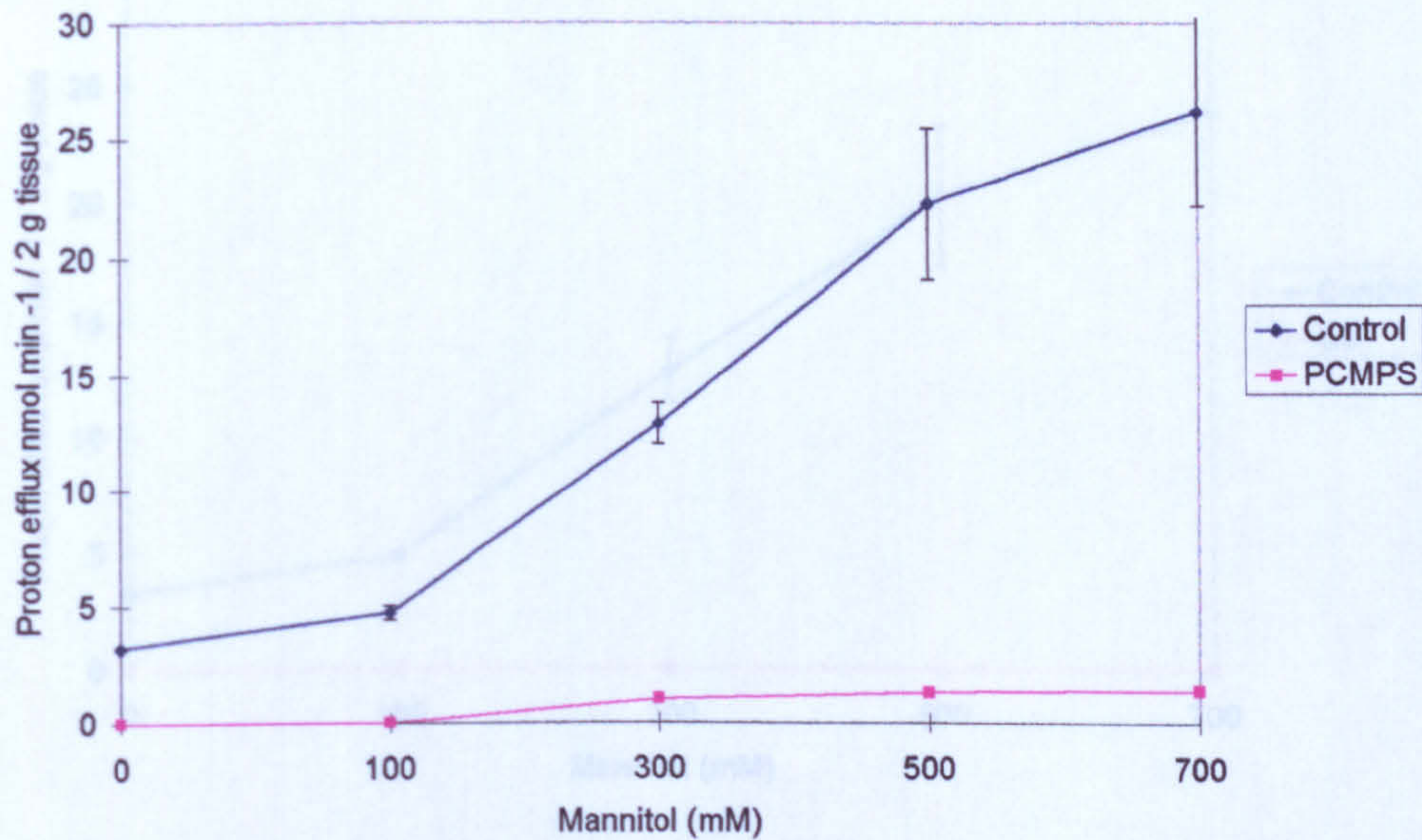
Mean proton efflux in sugar beet taproot tissue aerated in 10 ml of 0 - 700 mM mannitol, containing 0.5 mM  $\text{CaSO}_4$  and 2 mM KCl, in control and 1 mM KCN treated sugar beet discs, over 4 hours. Data are presented as mean and standard deviation of individual KOH additions, n is 5, 15, 25 and 30 in control 0 - 100 mM, 300 mM, 500 mM and 700 mM mannitol osmotica respectively. In KCN treated discs n is 1.





**Figure 6.9, Inhibition of proton efflux by PCMPS**

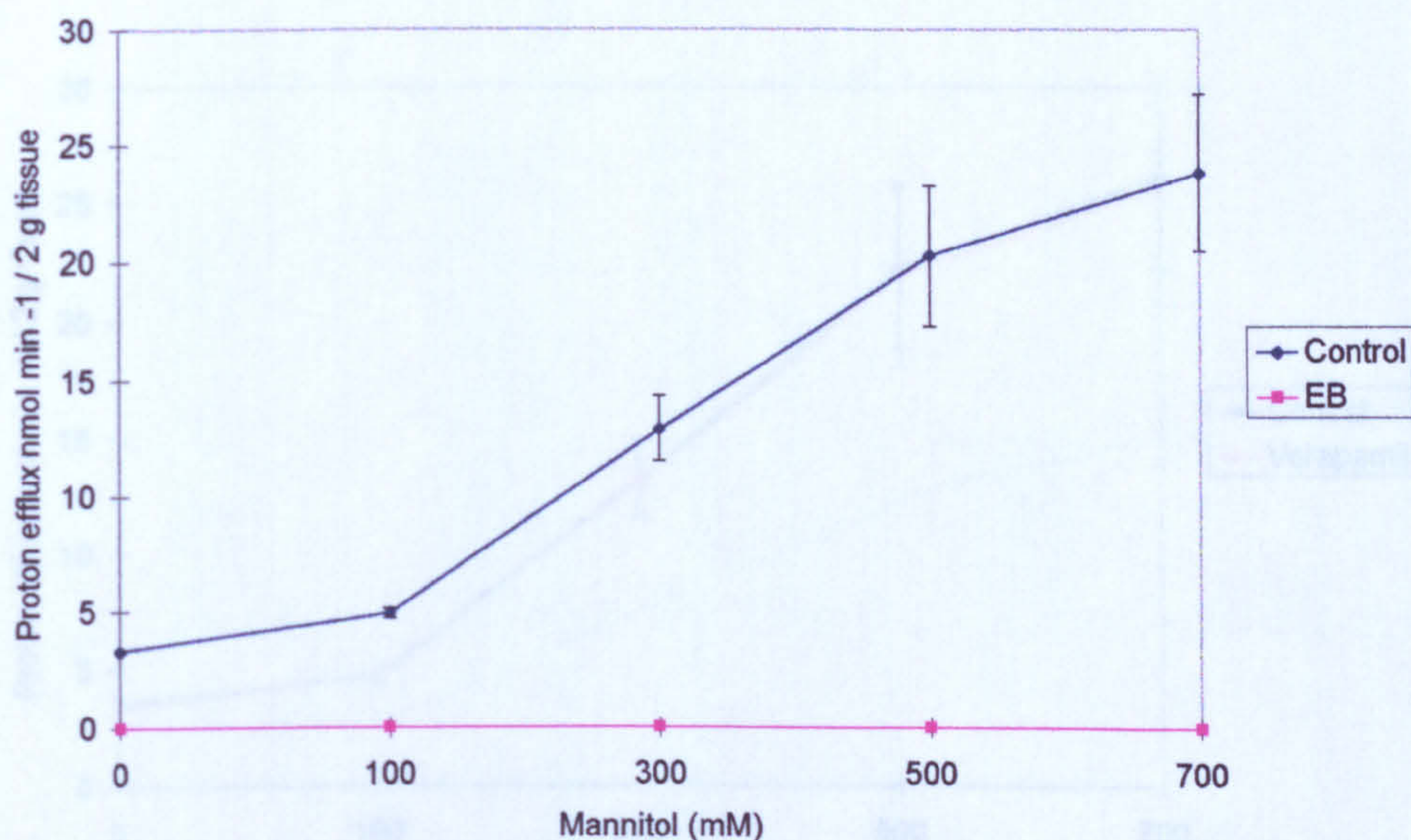
Mean proton efflux in sugar beet taproot tissue aerated in 10 ml of 0 - 700 mM mannitol, containing 0.5 mM  $\text{CaSO}_4$  and 2 mM KCl, in control and 1 mM PCMPS treated sugar beet discs, over 4 hours. Data are presented as mean and standard deviation of individual KOH additions, n is 5, 15, 25 and 30 in control 0 - 100 mM, 300 mM, 500 mM and 700 mM mannitol osmotica respectively. In PCMPS treated discs n is 1 and 5 in 0 - 100 mM and 300 - 700 mM mannitol osmotica respectively.





**Figure 6.10, Complete inhibition of proton efflux by erythrosin B (EB)**

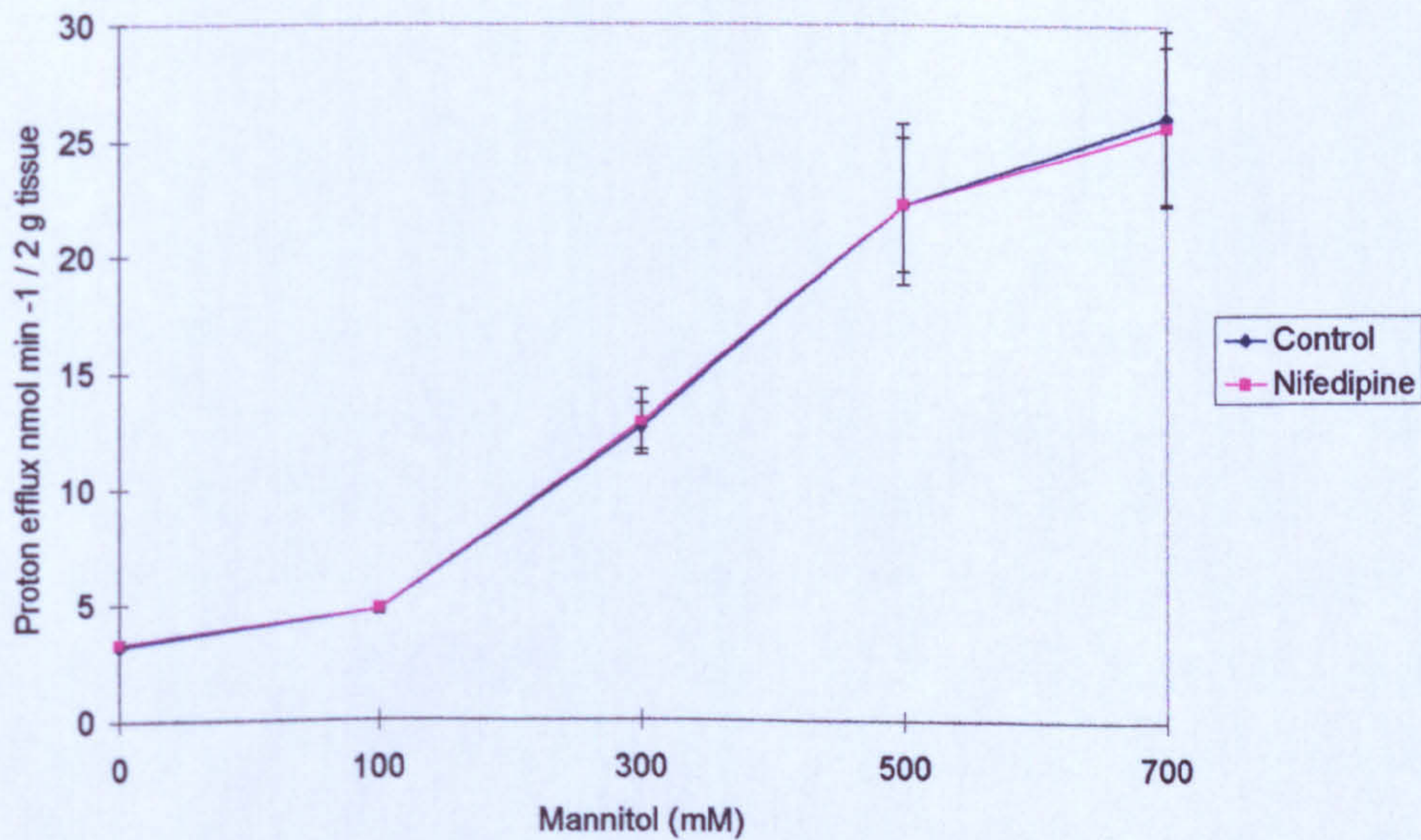
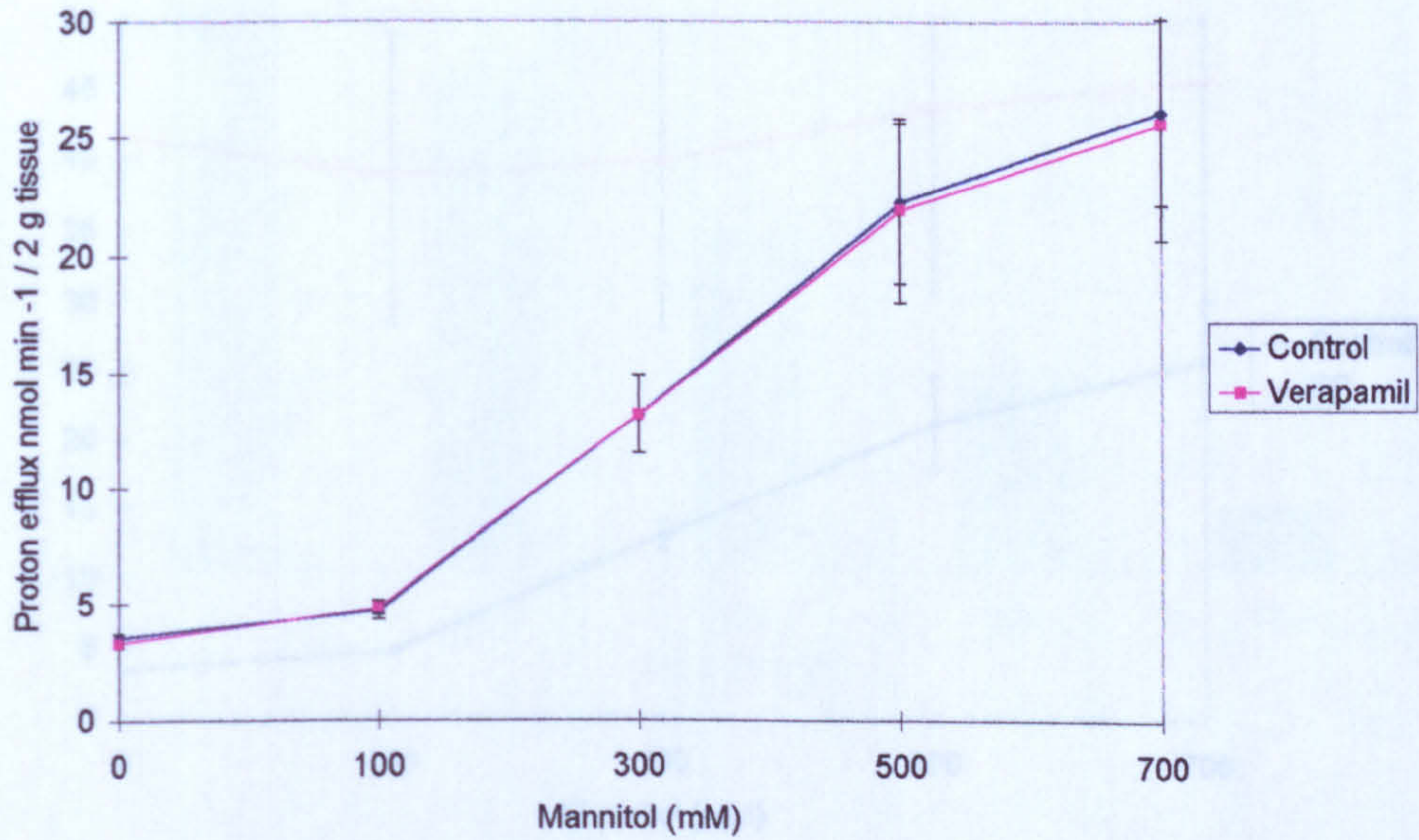
Mean proton efflux in sugar beet taproot tissue aerated in 10 ml of 0 - 700 mM mannitol, containing 0.5 mM  $\text{CaSO}_4$  and 2 mM KCl, in control and 100  $\mu\text{M}$  EB treated sugar beet discs, over 4 hours. Data are presented as mean and standard deviation of individual KOH additions, n is 5, 15, 25 and 30 in control 0 - 100 mM, 300 mM, 500 mM and 700 mM mannitol osmotica respectively. In EB treated discs n is 1.





**Figure 6.11 and 6.12, Proton efflux in the presence of verapamil and nifedipine**

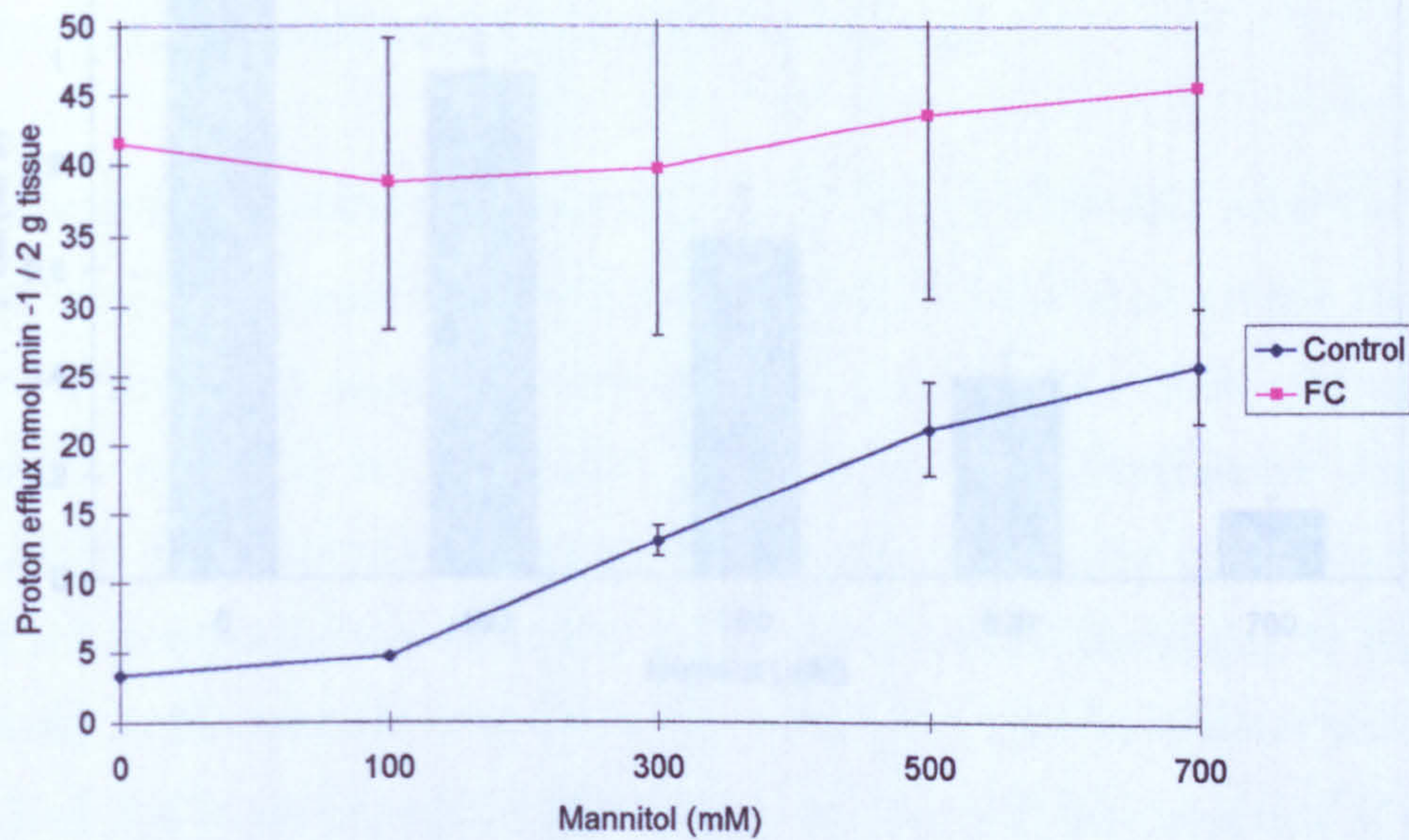
Mean proton efflux in sugar beet taproot tissue aerated in 10 ml of 0 - 700 mM mannitol, containing 0.5 mM  $\text{CaSO}_4$  and 2 mM KCl, in control and 100  $\mu\text{M}$  verapamil (**Figure 6.11**, upper figure) and nifedipine (**Figure 6.12**, lower figure) treated sugar beet discs, over 4 hours. Data are presented as mean and standard deviation of individual KOH additions, n is 5, 15, 25 and 30 in control and treated 0 - 100 mM, 300 mM, 500 mM and 700 mM mannitol osmotica respectively.





**Figure 6.13 , Proton efflux stimulation in the presence of fusicoccin (FC)**

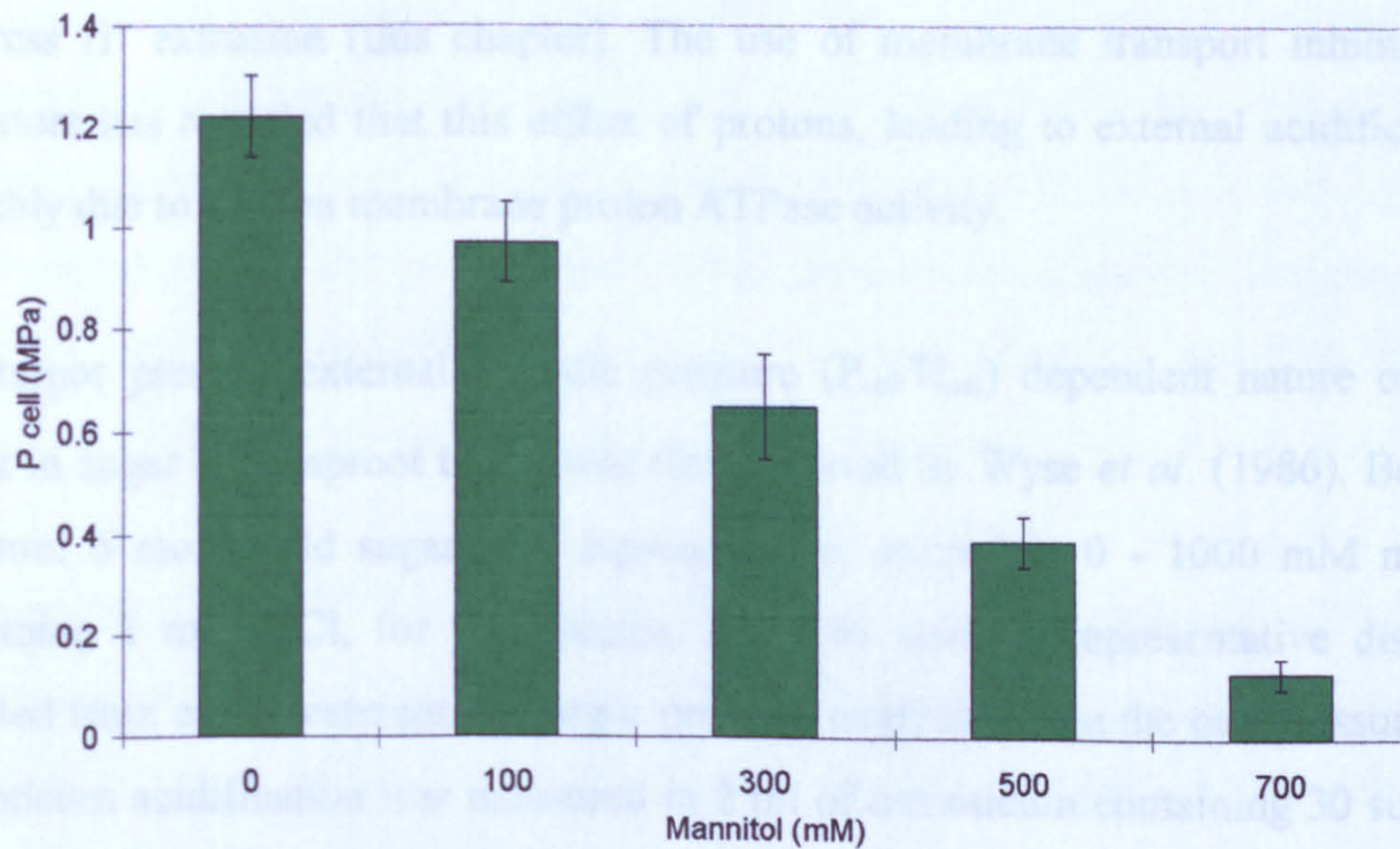
Mean proton efflux in sugar beet taproot tissue aerated in 10 ml of 0 - 700 mM mannitol, containing 0.5 mM  $\text{CaSO}_4$  and 2 mM KCl, in control and 10  $\mu\text{M}$  FC treated sugar beet discs, over 4 hours. Data are presented as mean and standard deviation of individual KOH additions, n is 5, 15, 25 and 30 in control 0 - 100 mM, 300 mM, 500 mM and 700 mM mannitol osmotica respectively. In FC treated discs n is 40 throughout.





**Figure 6.14, Turgor pressure ( $P_{cell}$ ) modulation by external mannitol**

Turgor pressure ( $P_{cell}$ ) in sugar beet taproot discs aerated in 0 - 700 mM mannitol, containing 0.5 mM  $CaSO_4$  and 2 mM KCl, for 4 hours. Data are presented as mean and standard deviation, n is 15 (5 beet discs, 3 cells per disc).



The data presented by Wyse *et al.* (1986) are largely in agreement with the data presented in this chapter; however, the Wyse *et al.* (1986) data points to an acidification optimum at a turgor pressure ( $P_{cell}$ ) of 0.3 MPa, whereas the data in this chapter suggests that acidification continues to decrease, with decreasing turgor pressure, below 0.3 MPa. The greatest rate of proton efflux was measured in sugar beet discs aerated in 700 mM mannitol, with a  $P_{cell}$  value of approximately 0.1 MPa. However, proton efflux did appear to be levelling out at this point, suggesting that a further decrease in  $P_{cell}$  may suppress any further increase in  $H^+$  extrusion. This discrepancy between the Wyse *et al.* (1986) data and the data presented here, may be attributed to the effect of the external osmoticum. The initial pH, and the magnitude of pH change over time due to proton efflux, is likely to affect membrane transport processes.



## 6.4, Discussion

Changing the turgor pressure of sugar beet taproot discs, using mannitol osmotica of varying concentration, modulates the rate of proton efflux from the tissue. A decrease in cell turgor pressure ( $P_{\text{cell}}$ ) stimulates proton efflux, whereas an increase in  $P_{\text{cell}}$  appears to suppress  $H^+$  extrusion (this chapter). The use of membrane transport inhibitors and activators has revealed that this efflux of protons, leading to external acidification, is probably due to plasma membrane proton ATPase activity.

The turgor pressure/external osmotic pressure ( $P_{\text{cell}}/\Pi_{\text{ext}}$ ) dependent nature of proton efflux in sugar beet taproot tissue was first reported by Wyse *et al.* (1986). Beet discs cut from 6 month old sugar beet taproots were aerated in 0 - 1000 mM mannitol, containing 1 mM KCl, for 90 minutes. After 90 minutes representative discs were sampled from each treatment for turgor pressure analysis, using the cell pressure probe. Osmoticum acidification was measured in 2 ml of osmoticum containing 30 sugar beet discs, using a pH electrode. The change in pH ( $\Delta$  pH) over 90 minutes was plotted against beet disc turgor pressure. Their findings revealed that the magnitude of external acidification was dependent on cell turgor pressure ( $P_{\text{cell}}$ ). Acidification increased as  $P_{\text{cell}}$  decreased, reaching an optimum level at 0.3 MPa ( $\Delta$  pH 0.7 - 1.0), before trailing off towards the lower extremes of cell turgor pressure.

The data presented by Wyse *et al.* (1986) are largely in agreement with the data presented in this chapter. However, the Wyse *et al.* (1986) data points to an acidification optimum at a turgor pressure ( $P_{\text{cell}}$ ) of 0.3 MPa, whereas the data in this chapter suggests that acidification continues to decrease, with decreasing turgor pressure, beyond 0.3 MPa. The greatest rate of proton efflux was measured in sugar beet discs aerated in 700 mM mannitol, with a  $P_{\text{cell}}$  value of approximately 0.1 MPa. However, proton efflux did appear to be levelling out at this point, suggesting that a further decrease in  $P_{\text{cell}}$  may suppress any further increase in  $H^+$  extrusion. This discrepancy between the Wyse *et al.* (1986) data and the data presented here, may be attributed to the pH of the external osmotica. The initial pH, and the magnitude of pH change over time due to proton efflux, is likely to affect membrane transport processes.



For example, the plasma membrane proton ATPase has a pH optimum of about 6.6 (Michelet and Boutry, 1995), any deviation from this pH value suppresses proton ATPase activity. Lanfermeijer and Prins (1994) presented data which showed the pH dependent nature of proton ATPase activity. At pH 5.5, 6.5, and 7.5 proton ATPase activity, in *Avena sativa* (oat) plasma membrane vesicles, was 2.0, 3.5, and 1.0  $\mu\text{mol min}^{-1} \text{mg}^{-1}$  protein respectively. In this chapter, the pH of the external osmotica were maintained within a narrow range (6.6 - 6.9) by frequent titration with KOH, thus ensuring that the only variable parameter in the system was  $P_{\text{cell}}/\Pi_{\text{ext}}$ . In the Wyse *et al.* (1986) investigation, and in the majority of proton efflux studies discussed below external acidification was allowed to continue unchecked over a period of time, thus introducing a second variable parameter (pH) into the system.

Kinraide and Wyse (1986) looked at the  $P_{\text{cell}}/\Pi_{\text{ext}}$  dependent nature of proton efflux in sugar beet taproot tissue by measuring the membrane electrical potential difference ( $E_m$ ) of tissue bathed in mannitol osmotica of varying concentration. Tapering wedges of tissue, approximately 6 mm in cross section, were excised from mature sugar beet taproots. The sugar beet tissue was bathed in a medium containing 1 mM NaCl, 1 mM  $\text{Ca}(\text{NO}_3)_2$ , 1 mM  $\text{KH}_2\text{PO}_4$ , 0.25 mM  $\text{MgSO}_4$  and 0 - 800 mM mannitol, at pH 5.0. Measurement of  $E_m$  was carried out using microelectrodes, as described by Kinraide and Etherton (1980). The data obtained revealed that membrane electrical polarity increased as the external mannitol concentration increased. At 0 mM, 400 mM and 800 mM mannitol concentrations, membrane  $E_m$  was  $-80 \pm 2$  mV,  $-129 \pm 4$  mV and  $-136 \pm 17$  mV respectively. These data reflect the more vigorous  $\text{H}^+$  extrusion from sugar beet taproot tissue at the lower end of the turgor pressure ( $P_{\text{cell}}$ ) range.

Turgor/external osmotic pressure ( $P_{\text{cell}}/\Pi_{\text{ext}}$ ) induced proton efflux has been reported in a number of other plant tissues. Reinhold *et al.* (1984) measured external acidification in mannitol osmotica containing *Senecio mikanioides* leaf segments. *Senecio mikanioides* leaves, approaching full expansion, were selected and the lower epidermis removed. The leaves were cut into 4 mm<sup>2</sup> sections and equilibrated for 90 minutes in 0.1 mM  $\text{CaSO}_4$ . After the equilibration period, 0.5 g aliquots of tissue were placed into 10 ml volumes of 0 - 300 mM mannitol, containing 0.2 mM  $\text{CaSO}_4$  and 10 mM KCl. The pH



of the osmotica was measured initially and after 3 hours, using a pH electrode. During this time the pH of the 0 mM and 300 mM mannitol osmotica decreased by 0.2 and 0.7 pH units respectively, indicating that the *Senecio mikanioides* leaf segments in the 300 mM mannitol osmoticum had an accelerated rate of H<sup>+</sup> extrusion.

Teodoro *et al.* (1998) measured  $P_{\text{cell}}/\Pi_{\text{ext}}$  dependent proton efflux in *Arabidopsis thaliana* cells (0.1 g ml<sup>-1</sup>) suspended in 0.5 mM BTP-MES buffer, pH 6.25, containing 0.5 mM CaSO<sub>4</sub>, 2 mM KCl and 0 - 400 mM mannitol. Cells were harvested from the culture medium and equilibrated in 0.5 mM BTP-MES buffer, pH 5.0, for 18 hours prior to mannitol treatment. Proton efflux ( $\mu\text{mol g}^{-1} \text{fw h}^{-1}$ ) was measured by back titration with NaOH, and plotted against concentration of mannitol (mM). Their findings revealed that *Arabidopsis thaliana* cells also exhibit  $P_{\text{cell}}/\Pi_{\text{ext}}$  dependent proton efflux. Proton efflux in the 0 mM mannitol osmoticum was below 5  $\mu\text{mol g}^{-1} \text{fw h}^{-1}$ , however, as the concentration of the external mannitol osmotica increased, proton efflux also increased, peaking at 15  $\mu\text{mol g}^{-1} \text{fw h}^{-1}$  in the 300 mM mannitol osmoticum, before decreasing to 14  $\mu\text{mol g}^{-1} \text{fw h}^{-1}$  in the 400 mM mannitol osmoticum. This pattern of proton efflux in *Arabidopsis thaliana* cells is comparable to the pattern of external acidification observed by Wyse *et al.* (1986), in sugar beet taproot tissue (see above).

Turgor/external osmotic pressure ( $P_{\text{cell}}/\Pi_{\text{ext}}$ ) dependent proton efflux is also induced by other osmotica such as polyethylene glycol (Curti *et al.*, 1993) and sorbitol (Reuveni *et al.*, 1987). Reuveni *et al.* (1987) found that hyper-polarisation of carrot cells and acidification of the external medium occurred following exposure of the cells to increasing external osmotic pressures, induced by sorbitol. Approximately  $6 \times 10^5$  cells were incubated in 15 ml of 0 - 800 mM mannitol, with 0.2 mM CaSO<sub>4</sub>, with shaking. Change in osmoticum pH was determined in cell free aliquots of the media at 60 minute intervals for 120 minutes. Membrane hyper-polarisation was determined by measuring the accumulation of tetraphenylphosphonium over the same time period. Acidification and membrane polarisation increased with increasing sorbitol concentration. Maximal hyper-polarisation and acidification ( $\Delta \text{pH } 0.5$ ) occurred at 200 mM sorbitol. At higher



sorbitol concentrations a decrease in acidification and membrane polarisation was observed.

The proton efflux data presented in this chapter, together with the proton efflux and external acidification data taken from the literature, demonstrate that many plant tissues respond to a turgor/osmotic related stimulus by modulating the rate of proton efflux from the cells. Active proton efflux from plant tissue is generally associated with plasma membrane proton ATPase activity (Serrano, 1989 and 1990; Michelet and Boutry, 1995). In this study, the role of the plasma membrane proton ATPase in  $P_{\text{cell}}/\Pi_{\text{ext}}$  dependent proton efflux in sugar beet taproot tissue was investigated using membrane transport inhibitors and activators.

In order to establish that  $P_{\text{cell}}/\Pi_{\text{ext}}$  dependent proton efflux in sugar beet taproot tissue is an ATP requiring process, beet discs were subjected to treatments designed to prevent ATP production, by inhibiting the respiratory chain. Briefly, ATP is generated by a process which couples electron-transfer with oxidative phosphorylation (Mitchell, 1979). Multiprotein electron-transfer complexes in the mitochondrial inner membrane reoxidise the NADH and FADH<sub>2</sub> generated by the citric acid cycle (Baldwin and Krebs, 1981) and fatty acid oxidation (Wakil *et al.*, 1983) in the adjacent mitochondrial matrix. These complexes pass electrons stepwise to molecular oxygen at the end of the chain. This flow of electrons is coupled indirectly, but tightly, to the synthesis of ATP; as electrons move through some of the electron-transfer complexes, protons are taken up from the solution from the solution in the mitochondrial matrix and released at the outer surface of the inner membrane, setting up a gradient of pH and electric potential across the membrane. Protons flow back into the mitochondrial matrix through an ATP-synthase enzyme, which uses the free energy liberated by the proton to drive ATP synthesis (see Hinkle and McCarty, 1978; Mitchell, 1979; Dickerson, 1980; Boyer, 1989; Chan and Li, 1990).

The citric acid cycle through to the electron-transfer chain and oxidative phosphorylation are all oxygen requiring processes. In the absence of oxygen (anoxia) aerobic respiration leading to ATP synthesis is inhibited. Potassium cyanide (KCN)



inhibits a specific site on the electron-transfer chain, the final electron-transfer complex - cytochrome oxidase (Nicholls, 1982). Each cytochrome is made up of a porphyrin ring, with a central iron atom (Dickerson, 1972). Negative ions such as  $\text{CN}^-$  and  $\text{N}_3^-$  interact with the ferric form of iron at the centre of the porphyrin ring, thus preventing the final stage of electron-transfer to molecular oxygen (see Nicholls, 1982; Nicholls and Ferguson, 1992). The inhibition of  $P_{\text{cell}}/\Pi_{\text{ext}}$  dependent proton efflux in sugar beet taproot discs subjected to anoxia and KCN is consistent with this mechanism being an oxygen and ATP requiring process (this chapter).

In order to determine the molecular basis of  $P_{\text{cell}}/\Pi_{\text{ext}}$  dependent proton efflux, specialised membrane transport inhibitors were selected, which target specific sites on the plasma membrane. P-Chloromercuriphenylsulphonic acid (PCMPS) is a non-penetrating chemical modifier, which targets sulfhydryl groups (-SH) on the plasma membrane (Giaquinta, 1976). It has been extensively employed to investigate surface-located carrier proteins involved in the transport of amino acids, sugars and ions in a variety of plant tissues, including sugar beet leaf discs (Giaquinta, 1976), *Vicia faba* leaves (Delrot *et al.*, 1980) and *Vicia faba* and *Pisum sativum* seed coats (Wolswinkel and Ammerlaan, 1983; De Jong *et al.*, 1996).

Many plant ATPases cannot function if their -SH group integrity has been compromised (Poole, 1978). Therefore, modulation of -SH groups on the plasma membrane proton ATPase is likely to suppress proton ATPase activity and inhibit the secondary transport of solutes, such as sucrose. Giaquinta (1976) demonstrated that PCMPS markedly inhibits sucrose uptake into sugar beet leaf tissues. Sucrose accumulation was determined by  $^{14}\text{C}$  analysis in sugar beet leaf discs incubated in 20 mM K-phosphate buffer (pH 7.0), containing varying concentrations of PCMPS. Sucrose accumulation in leaf discs, treated with 2 mM PCMPS for 15 minutes, decreased by 60 %. This inhibition of sucrose accumulation was not accompanied by a decrease in photosynthesis or respiration indicating that the site of PCMPS inhibition was confined to the plasma membrane. Giaquinta (1977) proposed that sucrose accumulation in sugar beet leaf tissue was facilitated by  $\text{H}^+$ /sucrose symport, driven by the plasma membrane proton ATPase (see also Giaquinta, 1983), and later, presented data demonstrating that



PCMPS also inhibits plasma membrane proton ATPase mediated proton efflux (Giaquinta, 1979). Approximately 2 g fresh weight of 0.5 cm<sup>2</sup> sugar beet leaf discs were incubated in 100 ml of 0.2 mM KH<sub>2</sub>PO<sub>4</sub>, 0.2 mM CaCl<sub>2</sub>, containing 0 - 0.5 mM PCMPS, at pH 6.0. After 15 - 20 minutes medium acidification was measured with a pH electrode and proton efflux determined by back titration with NaOH. Proton efflux in control treated sugar beet leaf tissue (in the absence of PCMPS) was 1.46  $\mu\text{mol g}^{-1} \text{fw h}^{-1}$ , whereas in the PCMPS treated tissue proton efflux was completely abolished. These data are in agreement with the data presented in this chapter. Proton efflux in sugar beet taproot tissue was largely abolished by 1 mM PCMPS throughout the range of mannitol treatments (this chapter).

Sulfhydryl groups are abundant on the plasma membrane (Rothstein, 1970). It is therefore likely that an -SH group modifier such as PCMPS interacts with the plasma membrane at numerous sites. Erythrosin B (EB - an iodinated derivative of fluorescein), on the other hand, is a specific membrane transport inhibitor, which targets the plasma membrane proton ATPase (Cocucci, 1986; Cocucci and Marré, 1986; Gimmler, 1988). In this study 100  $\mu\text{M}$  EB completely abolished proton efflux in sugar beet taproot tissue, indicating that turgor/external osmotic pressure ( $P_{\text{cell}}/\Pi_{\text{ext}}$ ) dependent proton efflux in this tissue is driven by the plasma membrane proton ATPase. Similar findings have been observed in radish seedlings (Cocucci and Marré, 1986), *Ricinus* cotyledons, cucumber hypocotyls (Ball *et al.*, 1987), *Elodea densa* leaves (Beffagna and Romani, 1988), and *Arabidopsis thaliana* cells (Curti *et al.*, 1993).

Cocucci and Marré (1986) demonstrated that a relatively low concentration of EB (100 - 300  $\mu\text{M}$ ) inhibits both basal and fusicoccin (FC) induced proton efflux, and depolarises the membrane potential, in 24 hour old radish seedlings. Proton efflux experiments were carried out on 1 g fresh weight of radish seedlings (approximately 50 seedlings) in 10 ml of 1 mM MES-K, 3 mM K<sub>2</sub>SO<sub>4</sub>, 0.5 mM CaSO<sub>4</sub>, pH 6.2, at 27 °C, with shaking, in the dark. Change in pH ( $\Delta$  pH) was determined with a pH electrode after 60 minutes. In control (without FC) and 100  $\mu\text{M}$  EB treated radish seedlings  $\Delta$  pH was  $-0.23 \pm 0.01$  and  $0.03 \pm 0.01$  respectively. In 10  $\mu\text{M}$  FC and 10  $\mu\text{M}$  FC plus 100  $\mu\text{M}$  EB treated radish seedlings  $\Delta$  pH was  $-1.20 \pm 0.04$  and  $-0.75 \pm 0.02$  respectively.



Transmembrane electric potential measurements were carried out on apical root segments (2 cm in length). Selected seedlings were aerated in 1 mM MES-K, 0.3 mM CaSO<sub>4</sub>, and 1 mM KCl prior to membrane potential determination in the same medium, at 22 °C. In control (without FC) and 10 μM FC treated radish seedlings membrane potential was -120 mV and -150 mV respectively. Addition of 300 μM EB to the FC treated seedlings depolarised the membrane, bringing the membrane potential value back to - 120 mV.

Beffagna and Romani (1988) reported the EB inhibition of K<sup>+</sup> and FC induced proton efflux in *Elodea densa* leaves. Mature *Elodea densa* leaves were harvested and incubated for 2 hours in 0.5 mM CaSO<sub>4</sub> solution at 20 °C, under agitation. After the incubation period the leaves (0.2 g fresh weight 10 ml<sup>-1</sup>) were transferred to a solution containing 0.5 mM CaSO<sub>4</sub>, 0.3 mM MES, 5 μM DCMU (a photosynthetic inhibitor), 2.5 mM K<sub>2</sub>SO<sub>4</sub>, 100 μM FC, and 0 - 300 μM EB. External acidification was measured with a pH electrode and proton efflux was determined by back titration with NaOH after 90 minutes. Their findings revealed that 100 μM - 300 μM EB completely inhibited external acidification and demonstrated that 30 μM EB completely abolished titratable H<sup>+</sup> extrusion.

Finally, Curti *et al.* (1993) demonstrated the EB inhibition of P<sub>cell</sub>/Π<sub>ext</sub> induced proton efflux in *Arabidopsis thaliana* cells. Freshly harvested cells (0.1 g ml<sup>-1</sup>) were agitated in 0.5 mM BTP-MES buffer, pH 6.25, containing 0.5 mM CaSO<sub>4</sub> and 0 - 150 mM mannitol. External acidification was determined with a pH electrode in cell free, 120 μl aliquots of osmoticum. The change in pH ( Δ pH) in control 0 mM and 150 mM mannitol treated cells, over 180 minutes, was -0.17 and -0.59 pH units respectively. Addition of 100 μM EB completely suppressed H<sup>+</sup> extrusion, resulting in a Δ pH of 0.50 and 0.43 in 0 mM and 150 mM mannitol respectively.

To summarise briefly, the respiratory chain inhibitors, anoxia and KCN demonstrated that P<sub>cell</sub>/Π<sub>ext</sub> dependent proton efflux in sugar beet taproot tissue is an oxygen and ATP requiring process. Inhibition of proton efflux by PCMPS and erythrosin B (EB) established that this H<sup>+</sup> extrusion mechanism is due to plasma membrane proton



ATPase activity (this chapter). Therefore, in conclusion, sugar beet storage parenchyma cells apparently respond to a turgor/osmotic related stimulus by modulating the activity of a major primary transporter - the plant plasma membrane proton ATPase. However, the mode of stimulus detection and signal propagation, leading to proton ATPase modulation has not been established.

Changes in cytosolic calcium concentrations have been implicated in the response of plants to a number of stimuli (Bush, 1995), including plant growth regulators (Felle, 1988; Gilroy *et al.*, 1990; Schroeder and Hagiwara, 1990; Hahm and Saunders, 1991; Gilroy and Jones, 1992), light (Chae *et al.*, 1990; Russ *et al.*, 1991), temperature (Knight *et al.*, 1991; Braam, 1992), touch (Knight *et al.*, 1991), salinity and drought (Knight *et al.*, 1997). It has been suggested that  $Ca^{2+}$  acts as an intracellular messenger, conveying information about the nature of a particular stimulus or stress impinging on a cell to target proteins that guide the cellular response (Bush, 1993 and 1995).

Levels of cytosolic calcium are established by  $Ca^{2+}$  uptake and extrusion mechanisms, in which both influx and efflux transporters are active. The balance between the  $Ca^{2+}$  transporters determines the  $Ca^{2+}$  concentration in the cytosol (Bush, 1993 and 1995). Observations of stimulus induced changes in cytosolic  $Ca^{2+}$  indicate that there is both short-term and long-term regulation of this uptake and extrusion mechanism. Short-term regulation leads to abrupt and usually transient changes in response to stimuli that suddenly and preferentially alter the activity of an influx or an efflux transporter. Long-term regulation on the other hand, leads to the establishment of resting or steady state levels of cytosolic  $Ca^{2+}$  and the restoration of the uptake/extrusion balance (Bush, 1993 and 1995).

The change in cytosolic  $Ca^{2+}$  induced by most stimuli is transient and involves short-term regulation (Bush, 1993 and 1995). Preventing  $Ca^{2+}$  influx into the cytoplasm, by blocking calcium channels should, in theory, prevent the propagation of a stimulus induced calcium signal. The possible role of  $Ca^{2+}$  in the turgor/osmotic response, leading to plasma membrane proton ATPase modulation was investigated using the calcium channel blockers verapamil and nifedipine.



Verapamil belongs to the phenylalkylamine family of molecules. A moderate to high density of phenylalkylamine receptor sites have been reported in maize (Harvey *et al.*, 1989), carrot (Graziana *et al.*, 1988) and courgette membranes (Andrejauskas *et al.*, 1985). Also partial purification of a verapamil binding protein from maize coleoptiles has been achieved by Harvey *et al.* (1989). Furthermore, it has been demonstrated that verapamil suppresses cytokinin and exogenous  $\text{Ca}^{2+}$  stimulated bud formation in the moss *Funaria* (Saunders and Hepler, 1982 and 1983) and inhibits  $\text{Ca}^{2+}$  influx into carrot microsomes (Graziana *et al.*, 1988) and *Amaranthus tricolor* protoplasts (Rengel and Elliott, 1992; Terry *et al.*, 1992).

Nifedipine belongs to the 1-4, dihydropyridines group of calcium channel blockers. Low levels of 1-4, dihydropyridine receptor proteins have been reported in pea shoot membranes (Hetherington and Trewavas, 1984). However, no 1-4, dihydropyridine receptor sites have been detected in carrot (Graziana *et al.*, 1988) or courgette (Andrejauskas *et al.*, 1985), which is consistent with the absence of effect of this type of calcium channel blocker on  $\text{Ca}^{2+}$  influx in these examples (Andrejauskas *et al.*, 1985; Graziana *et al.*, 1988). Despite these findings, Terry *et al.* (1992) demonstrated that nifedipine and related molecules affected plasma membrane cation outward rectifiers in *Amaranthus tricolor* protoplasts, causing a 50 % block of time-dependent current, at concentrations between 50 - 100  $\mu\text{M}$ . The phenylalkylamines were found to be consistently more potent, however, and capable of blocking all time-dependent outward currents at concentrations as low as 15  $\mu\text{M}$ .

Turgor/external osmotic pressure ( $P_{\text{cell}}/\Pi_{\text{ext}}$ ) dependent proton efflux was unaffected by 100  $\mu\text{M}$  verapamil and nifedipine. The pattern of proton efflux, throughout the range of mannitol osmotica, was indistinguishable from that of the control (this chapter). Assuming the calcium channel blockers used were effective, these data suggest that  $\text{Ca}^{2+}$  is not involved in the signal-transduction pathway, leading to plasma membrane proton ATPase modulation in this case. Knight *et al.* (1997), however, found that mannitol and NaCl treatments led to transient increases in cytoplasmic free calcium concentration (of up to 1.5  $\mu\text{M}$ ) in *Arabidopsis thaliana* seedlings *in vivo*. These



cytoplasmic calcium elevations were inhibited by pretreatment with the calcium channel blocker lanthanum.

The fungal toxin fusicoccin (FC) promotes H<sup>+</sup> extrusion in plant tissues, examples include, sugar beet taproot tissue (this chapter), *Arabidopsis thaliana* cells (Curti *et al.*, 1993; De Michelis *et al.*, 1996), radish seedlings (Cocucci and Marré, 1986; De Michelis *et al.*, 1996), maize coleoptiles (Jahn *et al.*, 1996) and *Avena* coleoptiles (Rayle, 1973; Senn and Goldsmith, 1988). It has been demonstrated that this FC induced stimulation of proton efflux is due to an increase in plasma membrane proton ATPase activity (Rasi-Caldogno and Pugliarello, 1985; Rasi-Caldogno *et al.*, 1986; Aducci *et al.*, 1988; Marra *et al.*, 1992; De Michelis *et al.*, 1996; Jahn *et al.*, 1996).

Jahn *et al.* (1996) measured FC induced external acidification and plasma membrane proton ATPase activity in *Zea mays* coleoptiles. Fifty coleoptiles were split and pre-incubated, with agitation, in 8 ml of 0.5 mM BTP-MES (pH 5.5), 0.1 mM KCl, 0.1 mM CaCl<sub>2</sub> and 0 - 5 μM fusicoccin. External acidification was measured using a pH electrode, over 60 minutes. After pre-incubation, plasma membranes were isolated from control and FC treated *Zea mays* coleoptile segments (see Larsson *et al.*, 1994). Proton ATPase activity was determined by assay, in which ATP hydrolysis was enzymatically coupled to the oxidation of NADH. The rate of ATP hydrolysis was measured as the absorbance decrease at 340 nm. Fusicoccin (5 μM) caused a dramatic decrease in medium pH, from 5.55 to 4.60 within 60 minutes. ATP hydrolysis increased by 100 %, from 0.5 ADP mg<sup>-1</sup> protein min<sup>-1</sup> in control plasma membrane preparations to 0.1 ADP mg<sup>-1</sup> protein min<sup>-1</sup> in FC plasma membrane preparations.

De Michelis *et al.* (1996) measured plasma membrane proton ATPase activity in control and fusicoccin (FC) treated *Arabidopsis thaliana* and *Raphanus sativus* (radish) seedlings. The seedlings were pre-treated in 0 - 5 μM FC for up to 3 hours, prior to plasma membrane fraction isolation, using a method described by Olivari *et al.* (1993) and Rasi-Caldogno *et al.* (1995). Plasma membrane proton ATPase activity was determined by measuring the release of P<sub>i</sub> from ATP according to the method of Ames (1966), at pH 7.5. Proton ATPase activity in *Arabidopsis thaliana* plasma membranes,



pre-treated *in vivo* with 0  $\mu\text{M}$  and 5  $\mu\text{M}$  FC, was 82  $\text{nmol min}^{-1} \text{mg}^{-1}$  protein and 330  $\text{nmol min}^{-1} \text{mg}^{-1}$  protein respectively. Radish plasma membrane fractions had a control (0  $\mu\text{M}$  FC) and FC treated proton ATPase activity of 53  $\text{nmol min}^{-1} \text{mg}^{-1}$  protein and 142  $\text{nmol min}^{-1} \text{mg}^{-1}$  protein respectively. Pre-treatment, *in vivo*, with 5  $\mu\text{M}$  fusicoccin resulted in a 300 % and 170 % increase in proton ATPase activity in plasma membrane fractions isolated from *Arabidopsis thaliana* and radish seedlings respectively.

Fusicoccin (FC) does not interact with the plasma membrane proton ATPase directly, but binds to a specific FC receptor site on the plasma membrane, which in turn interacts with the proton ATPase by displacing the enzymes C-terminus (Meyer *et al.*, 1989; De Michelis *et al.*, 1996; Jahn *et al.*, 1997). The C-terminus region of the ATPase is an auto-inhibitory domain; displacement of this domain activates the proton ATPase (Aducci *et al.*, 1995; Jahn *et al.*, 1997). The fusicoccin receptor site belongs to a family of proteins called 14-3-3 proteins (Marra *et al.*, 1994). The 14-3-3 family is a highly conserved class of hydrophilic proteins with multiple, often regulatory, functions in a wide range of organisms (for a review see Aitken, 1996).

In this study, 10  $\mu\text{M}$  fusicoccin (FC) maximised proton efflux in sugar beet taproot discs, throughout the range of mannitol concentrations, apparently abolishing the  $P_{\text{cell}}/\Pi_{\text{ext}}$  dependent properties of the system. This suggests that the site of turgor/osmotic responsiveness on the plasma membrane is either the same as or “up stream” from that of fusicoccin sensitivity. The fusicoccin receptor protein (14-3-3 protein) may hold the key to turgor/osmotic related stimulus detection in sugar beet taproots and other plant tissues. The 14-3-3 family of proteins and their mode of action are discussed further in the following chapter, Chapter 7.



## 6.5, Summary and conclusions

- ❑ Changes in cell turgor pressure ( $P_{cell}$ ), induced by mannitol osmotica of varying concentration, modulate the rate of proton efflux from sugar beet taproot tissue. An increase in  $P_{cell}$  inhibits proton efflux, whereas a decrease in  $P_{cell}$  stimulates proton efflux.
- ❑ Inhibition of this turgor/external osmotic pressure dependent ( $P_{cell}/\Pi_{ext}$ ) proton efflux mechanism by respiratory chain inhibitors (anoxia and KCN), confirms that this process requires oxygen and ATP.
- ❑ The plasma membrane proton ATPase inhibitors PCMPS and erythrosin B abolish proton efflux, throughout the range of mannitol osmotica, demonstrating that proton efflux is due to plasma membrane proton ATPase activity.
- ❑ From these data it is clear that sugar beet storage parenchyma cells respond to a turgor/osmotic related stimulus by modulating the activity of an important primary transporter - the plasma membrane proton ATPase.
- ❑ The possible involvement of calcium as a secondary messenger in the chain of events leading from stimulus detection to proton ATPase modulation is tentatively ruled out. The calcium channel blockers verapamil and nifedipine have no effect on proton efflux in this system.
- ❑ Fusicoccin maximises proton efflux and apparently abolishes the  $P_{cell}/\Pi_{ext}$  dependent nature of the mechanism. This suggests that the site of turgor/osmotic responsiveness on the plasma membrane is either the same as or “up stream” from that of fusicoccin stimulation.



## Chapter 7 : Final discussion and concluding remarks

### 7.1, Final discussion

The work carried out on *Suaeda maritima* L. Dum. and *Beta vulgaris* L. in this study demonstrates that changes in cell turgor pressure/external osmotic pressure ( $\Delta P_{\text{cell}}/\Delta \Pi_{\text{ext}}$ ) initiate a sequence of events leading to osmotic adjustment (protoplastic and/or apoplastic) and turgor regulation (see Chapter 3, 4 and 5). Cells are apparently responding to a hydrostatic or osmotic related stimulus by modulating membrane transport processes. In Chapter 6, evidence is presented which suggests that osmotic adjustment is achieved by turgor/external osmotic pressure ( $P_{\text{cell}}/\Pi_{\text{ext}}$ ) dependent modulation of plasma membrane proton ATPase activity. It is assumed that this, in turn, drives the secondary transport of solutes necessary to achieve osmotic adjustment. The  $P_{\text{cell}}/\Pi_{\text{ext}}$  dependent nature of solute transport has been widely documented in the literature, in a range of organisms - including bacteria, algae and higher plants.

#### 7.1.1, The turgor/external osmotic pressure dependent transport of solutes in bacteria, algae and higher plants

In a fluctuating external environment bacteria behave as perfect osmometers, with a reflection coefficient which is close to 1 (Csonka, 1989; Csonka and Hansen 1991). An increase in external osmotic pressure leads to water efflux and a decrease in turgor pressure, whereas a decrease in the concentration of the external medium leads to water influx and an increase in cell turgor pressure. Changes in cell turgor pressure induce a turgor dependent response which leads to osmotic adjustment of solutes within the cell and subsequent restoration of cell turgor pressure (for reviews see Csonka, 1989; Csonka and Hansen 1991).

*Escherichia coli*, for example, maintains turgor pressure ( $P_{\text{cell}}$ ) at 0.3 MPa, over a range of external osmotic pressures ( $\Pi_{\text{ext}}$ ). This is primarily achieved by turgor dependent adjustment of  $K^+$  (Laimins *et al.*, 1981). Potassium ions are the most prevalent cations



in the cytoplasm of bacteria, and consequently play an important role in osmotic adjustment and turgor regulation (Csonka, 1989). The internal  $K^+$  concentration in *Escherichia coli* is determined by the osmotic pressure of the external medium ( $\Pi_{ext}$ ), and ranges from 100 mM in dilute media to 600 mM in media with an osmolarity of 1200 mOsmoles  $kg^{-1}$  (Epstein and Schultz, 1965). Small increases in  $\Pi_{ext}$  are countered by accumulation of  $K^+$  (McLaggan *et al.*, 1994), however, larger increases in  $\Pi_{ext}$  also require the accumulation of glutamate (Csonka, 1989; Csonka and Hansen, 1991; McLaggan *et al.*, 1994).

The turgor dependent nature of membrane transport processes has been most comprehensively studied in the marine algae (Gutknecht, 1968; Zimmermann and Steudle, 1974; Cram, 1976; Kirst and Bisson, 1979). The marine algae regulate cell turgor pressure ( $P_{cell}$ ), in response to changes in the external medium, by modulating membrane transport processes, which leads to osmotic adjustment of the protoplast (Cram, 1976; Gutknecht *et al.*, 1978; Zimmermann, 1978). The main ions involved in osmotic adjustment are  $K^+$ ,  $Na^+$  and  $Cl^-$  (Kirst and Bisson, 1979).

In *Valonia*, for example, turgor regulation is achieved by modulation of an inwardly directed  $K^+$  pump (Steudle and Zimmermann, 1974; Hastings and Gutknecht, 1974). The turgor dependent nature of this transport mechanism was first demonstrated by Gutknecht (1968) in *Valonia ventricosa* cells. Using a pressure perfusion system, the turgor pressure ( $P_{cell}$ ) of the cell was increased from 0 MPa to 0.1 MPa. This 0.1 MPa increase in  $P_{cell}$  gave rise to a 70 % decrease in  $K^+$  influx ( $K^+$  efflux also increased slightly). Zimmermann and Steudle (1974) modulated  $P_{cell}$  in *Valonia* by increasing or decreasing the osmotic pressure of the external medium ( $\Pi_{ext}$ ). This work demonstrated that  $K^+$  influx continues to decrease steadily up to a pressure level of 0.2 MPa in cells of *Valonia utricularis*. Above this  $P_{cell}$  level  $K^+$  influx became increasingly independent of pressure. Potassium efflux, however, showed a remarkable and progressive increase over the entire pressure range; up to 0.5 - 0.6 MPa, which is the point at which larger cells usually burst (Zimmermann and Steudle, 1974; Zimmermann, 1977 and 1978). Conversely, decreasing turgor pressure ( $P_{cell}$ ) in *Valonia macrophysa* from 0.15 MPa (the  $P_{cell}$  level maintained over a range of external salinities *in vivo*) to 0.05 MPa leads



to a 300 % increase in  $K^+$  influx ( the decrease in  $P_{cell}$  was achieved by pressure perfusion in this case - Hastings and Gutknecht, 1974).

Chloride ( $Cl^-$ ) transport also exhibits turgor dependence in some species of marine algae. Work carried out by Bisson and Gutknecht (1975) and Graves and Gutknecht (1976) on *Codium decorticum* and *Halicystis parvula* respectively, suggests that turgor dependent  $Cl^-$  transport plays a key role in turgor regulation in these species; in both cases  $Cl^-$  influx is stimulated by a low  $P_{cell}$  and inhibited by a high  $P_{cell}$ .

There are several lines of evidence that turgor pressure ( $P_{cell}$ ) can affect ion transport in higher plants. Meidner and Edwards (1975) clearly demonstrated that turgor dependent fluxes are encountered when stomata open and close. Luttge *et al.*, (1975) suggested that the diurnal oscillations of malate levels in the crassulacean acid metabolism of *Bryophyllum daigremontianum* leaf cells may be subject to direct turgor pressure control. It is also believed that a similar phenomenon plays a key role in the circadian rhythm of  $K^+$  fluxes in the pulvinule cells of *Trifolium repens* (Scott and Gulline, 1975).

More recently, work carried out on sugar beet taproot tissue has demonstrated the turgor dependent nature of sucrose and  $K^+$  transport in this tissue (Wyse *et al.*, 1986; Bell and Leigh, 1996). Wyse *et al.* (1986) showed that cell turgor pressure ( $P_{cell}$ ) is an important sucrose uptake regulator in sugar beet taproot tissue. Changes in  $P_{cell}$ , induced by mannitol osmotica, resulted in the modulation of  $^{14}C$  sucrose uptake. Sucrose uptake was measured in beet discs bathed in 20 mM  $^{14}C$  sucrose in 25 mM MES/BTP pH 6.5 buffer, containing 0 mM or 400 mM Mannitol, over 60 minutes. Beet discs bathed in the control medium, which was devoid of mannitol, had a sucrose uptake rate of  $0.50 \pm 0.05 \mu\text{mol h}^{-1} \text{g}^{-1}$ , whereas the mannitol treated discs had a sucrose uptake rate of  $1.16 \pm 0.21 \mu\text{mol h}^{-1} \text{g}^{-1}$  (an increase of 132 %). Proton efflux, attributed to plasma membrane proton ATPase activity, was also found to be turgor dependent. A decrease in  $P_{cell}$  stimulated proton ATPase activity (with an optimum at 300 mM mannitol external concentration). Wyse *et al.* (1986) proposed that the secondary transport of sucrose is reduced at high  $P_{cell}$  as a result of inhibition of the plasma membrane proton ATPase.



The turgor/external osmotic pressure ( $P_{\text{cell}}/\Pi_{\text{ext}}$ ) dependent nature of the plant plasma membrane proton ATPase was demonstrated in Chapter 6.

Other authors have also highlighted the turgor dependent nature of sucrose transport in beet tissue. Ehwald *et al.* (1980) reported that the leakage of sucrose from slices of sugar beet was strongly reduced in solutions of high osmotic pressure (0.8 MPa and above), and Perry *et al.* (1987), working on red beet, found that solutes were leaked in proportion to their intracellular concentration following an increase in  $P_{\text{cell}}$ . However, Bell and Leigh (1996) took the investigation of turgor dependent membrane transport in beet taproot tissue a stage further. They investigated the effects of turgor pressure on transport at specific membranes, i.e. the plasma membrane and tonoplast. The solutes of interest in this study were sucrose and  $K^+$ . Sucrose and  $K^+$  fluxes were determined by  $^{14}\text{C}$  and  $^{86}\text{Rb}$  analysis respectively. Rubidium is an analogue of  $K^+$ , and there is generally little discrimination between them in terms of solute flux, for example in barley tissues (Epstein, 1966; Pitman *et al.*, 1974) and rye (White *et al.*, 1991). Bell and Leigh (1996) demonstrated that  $P_{\text{cell}}/\Pi_{\text{ext}}$  dependent sucrose and  $K^+$  transport across the tonoplast largely followed the same pattern. Sugar beet taproot discs were incubated in BTP/MES buffer (pH 6.5), containing 50 mM sucrose, 5 mM KCl, 1 mM  $\text{CaSO}_4$  and 0 mM/600 mM mannitol. A decrease in turgor pressure ( $P_{\text{cell}}$ ), induced by an increase in external mannitol concentration, resulted in an increase in the rate of both sucrose and potassium uptake into the vacuole. Sucrose and  $K^+$  influx was initially determined under steady state 0 mM/600 mM mannitol conditions for 60 - 100 minutes. After a maximum of 100 minutes, the beet discs were subjected to a 1.5 MPa step-up/step-down treatment, in which 0 mM mannitol beet discs were transferred to a medium containing 600 mM mannitol and vice versa. Sucrose and  $K^+$  influx was measured at intervals for a further 4 hours. The decrease in  $P_{\text{cell}}$ , induced by the step-up treatment, led to an increase in the rate of both sucrose and  $K^+$  uptake into the vacuole of 100 % and 70 % respectively (sucrose uptake increased from 1 to  $2 \mu\text{mol h}^{-1} \text{g}^{-1}$ , and  $K^+$  uptake increased from 0.75 to  $1.25 \mu\text{mol h}^{-1} \text{g}^{-1}$ ) within 4 hours.

Conversely, an increase in  $P_{\text{cell}}$ , induced by the step-down treatment, largely inhibited sucrose and  $K^+$  uptake into the vacuole and accelerated solute efflux out of the tissue.



For example, under 600 mM mannitol steady state conditions, the flux of  $K^+$  from the cytoplasm outward, into the apoplast/external osmoticum was  $2.33 \mu\text{mol g}^{-1} \text{h}^{-1}$ , a step-down into 0 mM mannitol resulted in a massive 340 % increase in  $K^+$  efflux to  $8 \mu\text{mol g}^{-1} \text{h}^{-1}$ .

At the plasma membrane, however, changes in  $P_{\text{cell}}/\Pi_{\text{ext}}$  elicited different sucrose and  $K^+$  transport responses. An increase in  $P_{\text{cell}}$ , induced by the 1.5 MPa step-down treatment decreased the rate of  $K^+$  uptake, but increased the rate of sucrose uptake over time (a decrease in  $P_{\text{cell}}$  was found to induce the opposite effect). Potassium transport across the plasma membrane, into the cytoplasm, in discs bathed in 0 mM and 600 mM mannitol osmotica was  $3 \mu\text{mol h}^{-1} \text{g}^{-1}$  and  $4 \mu\text{mol h}^{-1} \text{g}^{-1}$  respectively after 4 hours. Whereas sucrose uptake from the apoplast was  $12 \mu\text{mol h}^{-1} \text{g}^{-1}$  and  $5 \mu\text{mol h}^{-1} \text{g}^{-1}$  in 0 mM and 600 mM treated sugar beet discs respectively, after 5 hours. Therefore, although both sucrose and  $K^+$  may be lost from cells following an increase in turgor pressure ( $P_{\text{cell}}$ ), it appears that sucrose is selectively retrieved from the apoplast, but  $K^+$  is not. Given this scenario,  $K^+$  will tend to accumulate in the apoplast during adjustment to high  $P_{\text{cell}}$  in sugar beet storage taproots. The loss of osmotically active ions from the protoplast reduces  $P_{\text{cell}}$  by decreasing the internal osmotic pressure ( $\Pi_{\text{cell}}$ ) of the cell, but more importantly the accumulation of solutes in the apoplast increases apoplastic osmotic pressure ( $\Pi_{\text{wall}}$ ) and further facilitates  $P_{\text{cell}}$  reduction. These data add weight to the findings discussed in Chapter 3, 4, and 5, and further highlight the potential importance of the apoplast as an osmotic compartment.

Moving away from beet taproot tissue, another interesting example of turgor dependent membrane transport is described by Teodoro *et al.* (1998) in *Arabidopsis thaliana* cells. The authors demonstrated that hyper-osmotic stress (200 mM mannitol) rapidly reduces  $\text{Cl}^-$  efflux by up to 70 % (from  $0.48 \pm 0.05 \mu\text{mol g}^{-1} \text{FW}$  in control cells in 100 mM mannitol, to  $0.14 \pm 0.01 \mu\text{mol g}^{-1} \text{FW}$  in 200 mM mannitol treated cells, after 10-30 minutes). Inhibition of  $\text{Cl}^-$  efflux under these conditions was found to be independent of a mannitol induced stimulation of  $\text{Cl}^-$  influx, and was rapidly reversible after removal of the hyper-osmotic shock treatment. The inhibition of  $\text{Cl}^-$  efflux was accompanied by plasma membrane proton ATPase stimulation ( $\text{H}^+$  efflux). Both inhibition of  $\text{Cl}^-$  efflux



and  $H^+$  efflux were dependent on the concentration of mannitol in the external medium. These data point to a correlation between the inhibition of  $Cl^-$  efflux and proton extrusion. However, a direct relationship between the two is ruled out by Teodoro *et al.* (1998). The authors argue that if hyper-osmotic stress primarily reduces  $Cl^-$  efflux (leading to hyper-polarisation of the plasma membrane), proton ATPase activity should not be stimulated (see Bellando *et al.*, 1995). Conversely, if hyper-osmotic shock primarily stimulates proton ATPase activity (which would once again lead to hyper-polarisation of the membrane)  $Cl^-$  efflux should not be inhibited. Teodoro and co-workers (1998) also demonstrated that direct stimulation of the proton ATPase by the fungal toxin fusicoccin (FC) did not affect  $Cl^-$  efflux. This further strengthens the view that the inhibition of  $Cl^-$  efflux can not be a direct consequence of proton ATPase activity.

The hypothesis put forward by the Teodoro *et al.* (1998) to explain these findings, suggests that the first target of hyper-osmotic stress, in other words the turgor/osmotic sensor, may in fact be the  $Cl^-$  channel itself. Inactivation of the  $Cl^-$  channel would induce a decrease in  $Cl^-$  efflux and, consequently, lead to transmembrane electric potential ( $E_m$ ) hyper-polarisation. This change in  $E_m$  would then allow larger influxes of solutes such as  $K^+$  and  $Cl^-$  (symported by two protons) or a lower  $K^+$  efflux. Both the increase in intracellular  $K^+$  concentration (tending to reduce  $E_m$  hyper-polarisation) and the decrease in cytoplasmic pH due to the entry of protons accompanying the  $Cl^-$  anion would activate the plasma membrane proton ATPase (see Beffagna and Romani, 1991). Returning briefly to Chapter 5, the above hypothesis may explain the observed facilitation of turgor regulation in sugar beet taproot discs, under closed system conditions, in the presence of KCl (see Figure 5.7 and 5.9).

The Teodoro *et al.* (1998) paper suggests that an ion channel (in this case a  $Cl^-$  channel) may play a role in actually sensing turgor pressure and/or osmotic pressure changes. The turgor sensor reacts to a stimulus by directly or indirectly activating the plasma membrane proton ATPase which subsequently drives the secondary transport of solutes necessary to achieve osmotic adjustment and turgor regulation. It is to turgor-sensing mechanisms that this discussion now turns.



The evidence that turgor pressure can directly influence membrane transport (examples of which are discussed above) has led to an extensive discussion of the possible mechanisms involved in turgor-sensing (Zimmermann, 1977 and 1978; Bisson and Gutknecht, 1980; Tomos, 1988). The aim is to understand the individual steps taken in the transformation of a hydrostatic/osmotic signal into changes in membrane transport. The main consensus of opinion in the scientific community is that the basic steps of the turgor-sensing mechanism are mechanical and electrochemical in nature. This led to the formulation of the electromechanical turgor-sensing model (Zimmermann *et al.*, 1974; Coster and Zimmermann, 1975; Coster *et al.*, 1976; Zimmermann *et al.*, 1977; Zimmermann, 1977 and 1978). The fundamental concept behind this model is that mechanical forces can act on the mechanics of membranes in two ways: first by direct compression of the membrane, and secondly by membrane stretching induced by a pressure gradient across the membrane. In walled cells, stretching of the cell membrane in response to pressure gradients is controlled by the elastic properties of the cell wall to which the plasma membrane is coupled. Pressure gradient induced stretching may also change membrane thickness. The electromechanical model postulates that the pressure-induced changes in the geometric dimensions of the membrane, or certain membrane areas which may be preferentially involved in turgor sensing, are transformed into electrochemical changes within the membrane, which in turn lead to membrane transport.

Plasma membrane pressure-induced changes are beautifully illustrated in a paper by Peng and Jaffe (1976). They prepared freeze-fractures of a *Pelvetia* embryo plasma membrane over a range of cell turgor pressures. In a fully turgid cell, imprints of cell wall microfibrils were numerous and clearly visible. At intermediate turgor pressures microfibril imprints were still discernible, but much less prominent and less numerous. A fully plasmolysed cell showed no microfibril imprints whatsoever. These observations demonstrate that changes in turgor pressure induce physical changes in the plasma membrane/cell wall complex.

From the literature I propose that there are three possible candidates that could fulfil the role of a plasma membrane bound turgor-sensor in bacteria, algae and higher plants.



These are primary transporters such as the P-type ATPases, mechanosensitive ion channels, and molecular switches such as the 14-3-3 proteins.

### 7.1.2, Primary transporters as turgor-sensors

To regulate internal osmolarity, *Escherichia coli* accumulate  $K^+$  by two distinct transport mechanisms. Under most growth conditions  $K^+$  is taken up by the constitutive TrkA system, which has a high rate of transport and a low affinity for  $K^+$  (Rhoads *et al.*, 1976). At very low external  $K^+$  concentrations,  $K^+$  is taken up by the high-affinity Kdp system, which has a  $K_m$  of  $2 \mu M$  (Rhoads *et al.*, 1976). The Kdp system is ATP driven (Rhoads and Epstein, 1977) and requires the expression of four closely linked genes, Kdp A to D (Epstein and Davies, 1970; Rhoads *et al.*, 1978). Three of these genes, KdpA, KdpB and KdpC, form an operon that codes for three inner membrane proteins (Laimins *et al.*, 1978). The fourth gene, KdpD, codes for a positive regulator and is located on the promoter-distal end of the KdpABC operon (Rhoads *et al.*, 1978).

High external  $K^+$  represses the Kdp operon, whereas very low external  $K^+$  leads to Kdp operon expression (Laimins *et al.*, 1981). However, external  $K^+$  concentration is not believed to be the stimulus that leads to Kdp expression. The specific signal which leads to Kdp expression appears to be low turgor pressure ( $P_{cell}$ ), induced by an increase in the concentration of the external medium (Laimins *et al.*, 1981; Walderhaug *et al.*, 1992). At a given internal concentration of  $K^+$ , Kdp expression can be turned on or off by varying the medium  $K^+$  concentration, whereas at a given external  $K^+$  concentration, Kdp expression is dependent on the osmotic pressure of the external medium (Laimins *et al.*, 1981). The magnitude of Kdp expression is also determined by the magnitude of the osmotic shift in the external medium (Laimins *et al.*, 1981).

Control of expression by turgor pressure also explains the role of external  $K^+$  concentration in regulation of Kdp expression. Kdp expression occurs at an external  $K^+$  concentration which is low enough to adversely affect cell growth. When  $K^+$  uptake is inadequate (due to low  $K^+$  concentration in the external medium), the intracellular volume increases that accompany growth lead to a reduction in internal osmotic pressure. This reduction in internal osmotic pressure ( $\Pi_{cell}$ ) is accompanied by a



corresponding decrease in turgor pressure ( $P_{\text{cell}}$ ) which in turn leads to Kdp expression (Laimins *et al.*, 1981; Walderhaug *et al.*, 1992).

The Kdp transport system in *Escherichia coli* is a  $K^+$  ATPase, a member of the  $E_1 - E_2$  class of transport ATPases (Skou, 1975; Inesi, 1985). These particular transport ATPases are also often referred to as P-type ATPases (Pederson and Carafoli, 1987) to distinguish them from ATPases that do not form a phosphorylated intermediate (Epstein *et al.*, 1990).

Another well documented turgor dependent P-type ATPase is the plant plasma membrane proton ATPase (see Chapter 6). As a key primary transporter it is believed to play a central role in osmotic adjustment (Reinhold *et al.*, 1984; Serrano, 1989 and 1990; Michelet and Boutry, 1995). The turgor/external osmotic pressure ( $P_{\text{cell}}/\Pi_{\text{ext}}$ ) dependent nature of the plasma membrane proton ATPase is demonstrated and discussed in Chapter 6. To briefly recap, a decrease in turgor pressure ( $P_{\text{cell}}$ ), induced by an increase in the concentration of the external medium ( $\Pi_{\text{ext}}$ ), leads to plasma membrane proton ATPase stimulation, whereas an increase in  $P_{\text{cell}}$  inhibits proton ATPase activity.

Reinhold *et al.* (1984) proposed that the operation of the plasma membrane proton ATPase is directly affected by the hydrostatic pressure gradient across the plasma membrane/cell wall complex, possibly due to deformation of the plasma membrane by the cell wall. An increase in proton ATPase activity, directly induced by physical changes in the membrane, would generate the pH and electrochemical gradient (or proton-motive force) necessary to drive the secondary transport of solutes across the plasma membrane and thus achieve osmotic adjustment (see Serrano, 1989 and 1990; Michelet and Boutry, 1995). The benefit of a single detector/effector was also pointed out by Reinhold *et al.* (1984). The dual functioning of a system, both as detector of changes in cell turgor pressure ( $P_{\text{cell}}$ ) and effector of changes in cell osmotic pressure ( $\Pi_{\text{cell}}$ ) and/or wall osmotic pressure ( $\Pi_{\text{wall}}$ ), would obviate the postulated need for information transfer between detector and effector.



### 7.1.3, Mechanosensitive ion channels as turgor-sensors

Mechanosensitive channels have been found in a variety of animal cell types, as well as microbial and plant cells (for a review see Morris, 1990). In walled cells, such as *Escherichia coli* (Martinac *et al.*, 1987; Delcour *et al.*, 1989), yeast (Gustin *et al.*, 1988), and cultured tobacco cells (Falke *et al.*, 1988). However, the study of stretch activated or mechanosensitive ion channels has mainly concentrated on stomatal guard cells. Changes in guard cell volume and pressure can be large (3 : 1 volume change and more than 1 MPa pressure change) and are largely controlled by the release and uptake of ions, principally  $K^+$ , malate and  $Cl^-$ , through co-ordination of ion channels and ion pumps (Raschke, 1979; Outlaw, 1983; Zeiger, 1983; Macrobbie, 1988; Hedrich and Schroeder, 1989; Mansfield *et al.*, 1990). Guard cells deal with a variety of internal and external stimuli (light,  $CO_2$ , plant water status, and growth regulator concentration) and adjust the stomatal aperture accordingly. This would suggest that they possess a sophisticated and finely tuned mechanism for regulating volume and turgor pressure (Raschke, 1970; Farquhar *et al.*, 1978).

The role of mechanosensitive channels in turgor pressure regulation was investigated by Cosgrove and Hedrich (1991). Using the patch clamp technique in *Vicia faba* leaves they examined guard cells for mechanosensitive channels which might respond to plasma membrane deformations that accompany changes in cell turgor pressure. Such channels could include both stretch-activated and stretch-inactivated channels. The work carried out by Cosgrove and Hedrich (1991) identified three stretch-activated channels (one of each for  $Cl^-$ ,  $K^+$  and  $Ca^{2+}$ ). They were distinguishable from their non stretch-activated counterparts with respect to their conductance, selectivity and kinetics, as well as in their sensitivity to membrane tension. Compared to other cells (see Morris, 1990), guard cells have an unprecedented variety of mechanosensitive channels; which suggests that guard cells possess multiple, highly specialised mechanisms for sensing and controlling turgor pressure.

In the plasma membrane of other walled cells, stretch-activated channels have been characterised with lower ion specificity, larger amplitudes, and/or larger mean opening times than the guard cell stretch-activated channels. These properties indicate that the



channels in these other cells act directly as pressure valves against excessive pressure (Morris, 1990; Cosgrove and Hedrich, 1991). For example: cultured tobacco cells have a stretch-activated anion channel with a single channel conductance 5 - 10 times larger than the equivalent stretch-activated channel found in guard cells, an open time 100 times longer, and less selectivity for Cl<sup>-</sup> over K<sup>+</sup> (Falke *et al.*, 1988; Cosgrove and Hedrich, 1991). The yeast stretch-activated channel has a conductance (40 pS) similar to values found for some guard cell stretch-activated channels, but has poor ion selectivity and longer open times (Gustin *et al.*, 1988). More extreme is the stretch-activated channel reported for *Escherichia coli*, with a conductance of 1000 pS, negligible ion selectivity, and long open times (Martinac *et al.*, 1987; Delcour *et al.*, 1989). In animal cells, stretch-activated channels are similar in many ways to those found in guard cells; having a lower conductance, shorter open times and greater ion selectivity (reviewed in Morris, 1990).

#### 7.1.4, 14-3-3 type proteins as turgor-sensors

The 14-3-3 proteins initially were described as a part of an extensive characterisation of the acidic, soluble proteins within the mammalian brain (Moore and Perez, 1967). The study involved the purification of brain proteins of unknown function; names were assigned based on banding patterns on electrophoresis gels. The interesting observations at the time were that many of the proteins (including the 14-3-3 proteins) were abundant in the brain (up to 1 % of the total soluble protein in the case of 14-3-3 proteins), were found exclusively in the brain, and were immunologically conserved among animals. This led to the conclusion that 14-3-3 proteins were uniquely important to brain and neuronal function (Boston *et al.*, 1982 {a} and {b}; Erikson and Moore, 1980; Ichimura *et al.*, 1991).

By the mid 1980s the 14-3-3 proteins were understood to be a heterogeneous family of proteins with subunit masses of 30 kDa and with various isoelectric points ( Yamauchi *et al.*, 1981; Ichimura *et al.*, 1988). It was also known that they were found as dimers of 50 - 60 kDa in their native form and that their amino termini were blocked (Ichimura *et al.*, 1988). The first clue to 14-3-3 protein function came in 1987. Ichimura and co-workers (1987) observed that 14-3-3 proteins were similar in amino acid



composition to a protein known to activate tyrosine and tryptophan hydroxylases. Later experiments confirmed that the biochemical characteristics of 14-3-3 proteins were indistinguishable from those of purified activators of tyrosine and tryptophan hydroxylases (Ferl, 1996). Tyrosine and tryptophan hydroxylases are the first enzymes in the metabolic pathways that lead to serotonin and dopamine production; important neurotransmitters. This provided the scientific community with an important clue to 14-3-3 protein function - signal transduction (Ichimura *et al.*, 1987; Ferl, 1996).

More recently, 14-3-3 proteins have been discovered in many biological systems. They are not brain specific, or indeed animal specific. They are highly conserved and found in a broad range of tissues. Different isoforms have different functions, and no eukaryotic cell type has been identified which does not contain members of the 14-3-3 protein family (Robinson *et al.*, 1994; Ferl, 1996). It would be impossible to assign a single function to the 14-3-3 proteins, however, it is clear that they play an important and crucial role in signal transduction and regulation ( reviewed by Ferl, 1996).

A variety of external stimuli are known to influence 14-3-3 protein expression in higher plants. *Arabidopsis thaliana* has cold-inducible 14-3-3 proteins, expressed in stems, leaves and flowers at 4 °C (Jarillo *et al.*, 1994). Hypoxia induces a 300 % increase in the 14-3-3 protein, GF14-12, in *Zea mays* (De Vetten and Ferl, 1995). A tobacco homolog 14-3-3 protein is down regulated during acclimation to high NaCl (Chen *et al.*, 1994), and a rice isoform is regulated by both salt and low temperature (Kidou *et al.*, 1993). A barley 14-3-3 homolog is induced after infection with the powdery mildew fungus *Erysiphe graminis*, apparently linking pathogen attack to signal transduction (Brandt *et al.*, 1992). Shinozaki and Yamaguchi-Shinozaki (1997) include 14-3-3 type proteins in a list of other important regulatory proteins, expressed in response to water stress.

The 14-3-3 proteins regulate the plant enzyme nitrate reductase (Sehnke and Ferl, 1996). Nitrate reductase catalyses a key step in nitrate assimilation - the reduction of absorbed nitrate to nitrite (Campbell, 1996). The expression of nitrate reductase is inducible and depends on both a light signal and the presence of the substrate nitrate. The enzyme is also subject to post-transcriptional regulation by phosphorylation in response to stimuli such as light levels, CO<sub>2</sub> concentration, and nitrate availability



(Campbell, 1996). Nitrate reductase can be inactivated in a matter of hours in response to darkness. This inactivation occurs by a two step process: phosphorylation of the enzyme, followed by binding to an inhibitory protein (Spill and Kaiser, 1994; Douglas *et al.*, 1995; Su *et al.*, 1996; Bachmann *et al.*, 1996). Binding of the nitrate reductase inhibitory protein (NIP) only takes place in the presence of adequate  $Mg^{2+}$  (Sehnke and Ferl, 1996). Once binding has occurred it is believed that the NIP specifically interferes with electron flow between the two metal-dependent cofactor domains of nitrate reductase (Bachmann *et al.*, 1996), presumably by altering its conformational state. Nitrate reductase is reactivated upon dephosphorylation and release of the NIP. The NIP protein is a member of the 14-3-3 family of proteins (Bachmann *et al.*, 1996; Moorhead *et al.*, 1996).

Another known association of 14-3-3 proteins in plants is with the fungal toxin, fusicoccin (Korthout and De Boer, 1994). Fusicoccin causes wilt in almost all higher plants, because it induces stomatal opening and thus water loss. This phytohormone-like effect, and other associated physiological effects of fusicoccin, have been attributed to the activation of the plant plasma membrane proton ATPase (Johansson *et al.*, 1993; De Michelis *et al.*, 1996; see also Chapter 6). Moorhead *et al.* (1996) showed that fusicoccin can disrupt binding of 14-3-3 proteins to phosphorylated nitrate reductase, suggesting there is competition for binding domains on the 14-3-3 protein. These findings, and the report that the plasma membrane proton ATPase is regulated by phosphorylation (Xing *et al.*, 1996), suggests a possible mechanism of proton ATPase activation by fusicoccin. It is suggested that fusicoccin competes for, and removes, inhibitory 14-3-3 proteins from the plasma membrane proton ATPase molecules, thus initiating activation.

Taken together, the nitrate reductase and proton ATPase studies point to a common mechanism for enzyme regulation by 14-3-3 proteins. The target enzyme would be regulated by phosphorylation and binding of a 14-3-3 protein; this process would be contingent upon the cellular levels of 14-3-3 protein, the kinase and phosphatase that act on the target enzyme, and  $Mg^{2+}$  availability. This complex contingency, along with the large number of possible 14-3-3 isoform combinations (10 identified to date in



*Arabidopsis thaliana* - Sehnke and Ferl, 1996), allows for multiple regulatory controls on target enzyme activity (Sehnke and Ferl, 1996).

In addition to the regulatory functions of 14-3-3 proteins in plants, it is becoming increasingly apparent that 14-3-3 proteins also have a sensory function. Moorhead *et al.* (1996) speculated that the NIP 14-3-3 protein (discussed above) directly senses changes in nitrate reductase activity. Furthermore, the plasma membrane bound, fusicoccin sensitive 14-3-3 protein (which directly interacts with fusicoccin molecules), was designated a true receptor/sensory type protein by Aducci *et al.* in 1995. In Chapter 6, it was suggested that this fusicoccin-sensitive 14-3-3 protein may also be involved in turgor pressure and/or osmotic pressure perception at the plasma membrane. Sadly, there is no molecular evidence to back up this hypothesis as yet (see Ingram and Bartels, 1996).

Given the highly conserved nature and abundance of 14-3-3 proteins in plant tissue (Ferl, 1996), it is reasonable to conclude that 14-3-3 proteins are essential molecular switches which respond to a number of stimuli, by initiating a regulatory response. The extent and range of these stimuli has yet to be determined. However, in the search for a hydrostatic/osmotic sensor on the plasma membrane, I believe the membrane bound 14-3-3 proteins are a sensible place to start.



## 7.2, Concluding remarks and future work

The primary aim of this study was to establish the importance of the apoplast as an osmotic compartment in two members of the family *Chenopodiaceae* - *Suaeda maritima* L. Dum. and *Beta vulgaris* L. I believe that my endeavours to achieve this objective have been successful. A water relations study, at single cell resolution, revealed that osmotically active solutes accumulate, and are maintained at relatively high concentrations, in the apoplast/cell wall of these species. These apoplastic solutes are instrumental in maintaining cell turgor pressure ( $P_{\text{cell}}$ ) at a level which is much lower than the cell osmotic pressure ( $\Pi_{\text{cell}}$ ). Furthermore the accumulated apoplastic solutes are apparently under the full control of the cell, and are rapidly adjusted in response to changes in cell turgor pressure ( $\Delta P_{\text{cell}}$ ), induced by modulation of the concentration of the external medium ( $\Delta \Pi_{\text{ext}}$ ).

*Suaeda maritima* leaf epidermal cells accumulate NaCl in response to an increase in external NaCl. This protoplasmic osmotic adjustment mechanism, necessary to maintain water flux into the plant, is accompanied by a simultaneous adjustment of apoplastic solutes, enabling the leaf epidermal cells to maintain a constant turgor pressure ( $P_{\text{cell}}$ ) throughout (Chapter 3 and 4). Increases in *Beta vulgaris* (sugar beet) storage parenchyma cell osmotic pressure ( $\Pi_{\text{cell}}$ ), due to sucrose accumulation, is also apparently countered by the accumulation and adjustment of solutes in the apoplast, allowing  $P_{\text{cell}}$  to be maintained at a constant level (Chapter 5).

The elegant single cell techniques (see Chapter 2) utilised during this study allowed the direct measurement of cell turgor pressure ( $P_{\text{cell}}$ ), cell osmotic pressure ( $\Pi_{\text{cell}}$ ), and cell solute content, from which indirect inferences were made about the apoplastic milieu. However, the tantalising challenge of directly measuring apoplastic solute fluxes during osmotic adjustment still remains. The apoplastic spaces of a plant are manifold and their ionic environments are difficult to gain access to. In spite of this, ion-selective microelectrodes have been applied successfully to measure apoplastic free ion concentration in leaves and roots. Bowling (1987) measured the apoplastic activities of  $K^+$  and  $Cl^-$  in the leaf epidermis of *Commelina communis* in relation to stomatal activity.



Rhythmic and light-dependent  $K^+$  and  $Cl^-$  fluxes have been measured in the pulvini of *Samanea saman* (Lee and Satter, 1989) and *Phaseolus vulgaris* (Starrach and Mayer, 1989). In roots, Henriksen *et al.* (1992) measured net fluxes of  $NH_4^+$  and  $NO_3^-$  in the unstirred layer immediately external to the root surface in barley seedlings, and Felle (1998) measured apoplastic pH,  $K^+$  and  $Ca^{2+}$ , under varying conditions, in the root cortex of *Zea mays*.

The use of ion-selective microelectrodes in conjunction with the closed system method described in Chapter 4 and 5 could further facilitate the direct measurement of solute fluxes in the apoplastic compartment. Applying the closed system to excised tissue allows the researcher to access the apoplast of plant tissues which would otherwise be out of reach. The closed system maintains an apoplastic environment, in terms of volume, which is comparable to the apoplast *in vivo*, and also allows an element of control over the initial free solute content of the apoplast, which is simply not possible in intact tissues. Given the opportunity to continue working on the apoplastic compartment of higher plants, I would first seek to exploit the closed system as a possible tool to enhance and complement the fascinating work already carried out using ion-selective microelectrodes.

Turning from the measurement of protoplasmic/apoplastic osmotic adjustment to the molecular basis of these regulatory mechanisms - protoplasmic and apoplastic osmotic adjustment is largely achieved by the modulation and manipulation of membrane transport processes. The data presented in Chapter 6 suggests that the secondary transport of solutes necessary to achieve osmotic adjustment (in either the protoplasmic or apoplastic compartment) is driven by the turgor/external osmotic pressure ( $P_{cell}/\Pi_{ext}$ ) dependent nature of the plasma membrane proton ATPase. However, how the cell perceives changes in  $P_{cell}/\Pi_{ext}$  remains a mystery that only the molecular biologists can realistically tackle. In Chapter 6, I proposed that a plasma membrane bound, fusicoccin sensitive, 14-3-3 type protein may play a role in  $P_{cell}/\Pi_{ext}$  sensing. In order to establish whether this is the case or not, the development of genetically modified plants, which are devoid of this particular protein would certainly be useful. The current



understanding of the molecular basis of water stress tolerance in plants is reviewed by Ingram and Bartels (1996).



## Appendix

<b>In text</b>	<b>Address</b>
<i>Agaraid</i> s	Agaraid, Stansted, Essex. UK.
<i>BDH</i>	BDH Ltd., Poole, Dorset, UK.
<i>Beaudouin, Paris</i>	Beaudouin, 1-3 Rue Rataud, Paris.
<i>Cheshire Rubber Co.</i>	Cheshire Rubber Company, Unit 4-5, Alexander House, CCE Centre, Windmill Lane, Manchester, UK.
<i>Clarke Electromedical Instruments</i>	Clarke Electromedical Instruments, Reading, UK.
<i>Decon Laboratories Ltd.</i>	Decon Laboratories Ltd., Conway Street Hove, East Sussex, UK.
<i>Druck Ltd.</i>	Druck Ltd., Fir Tree Lane, Groby, Leicester, UK.
<i>Fisher Scientific</i>	Fisher Scientific UK., Bishop Meadow Road, Loughborough, Leicestershire, UK.
<i>Hamilton Co.</i>	Hamilton Company, Reno, Nevada, USA.
<i>Harvard Apparatus</i>	Harvard Apparatus, Sheerness, Kent, UK.
<i>Intracel Ltd.</i>	Intracel Ltd., Unit 4, Station Road, Shepreth, Royston, Herts., UK.
<i>Leica</i>	Leica Ltd., Milton Keynes, UK.
<i>Leitz</i>	Ernst Leitz Wetzlar GmbH, D-6330 Wetzlar, Germany.
<i>Moore and Wright</i>	Moore and Wright Micrometer Head Tools Ltd., Sheffield, UK.
<i>Portex Ltd.</i>	Portex Ltd., Hythe, Kent, UK.
<i>Prior Scientific Instruments</i>	Prior Scientific Instruments Ltd., Unit 4, Wilberham Road, Fulbourn, Cambridge, UK.



<i>Rathburn Chemicals</i>	Rathburn Chemicals Ltd., Walkerburn, Scotland, UK.
<i>RS Components</i>	RS Components Ltd., Corby, Northamptonshire, UK.
<i>Sigma Chemicals</i>	Sigma-Aldrich Chemicals, Fancy Road, Poole, Dorset, UK.
<i>TAAB Laboratory Equipment</i>	TAAB Laboratory Equipment Ltd., 3 Minerva House, Calleva Industrial Park, Aldermaston, Berkshire, UK.
<i>Terumo</i>	Terumo Europe, N.V. 3001 Leuven, Belgium.
<i>Wacker Chemicals Ltd.</i>	Wacker Chemicals Ltd., Walton on Thames, UK.
<i>Whatman</i>	Whatman International Ltd., Maidstone, Kent, UK.



## Literature cited

Aducci P., Ballio A., Blein I P., Fullone M. R., Rossignol M. and Scalla R. (1988). Functional reconstitution of a proton-translocating system responsive to fusicoccin. *Proceedings of the National Academy of Sciences in the USA* 85: 7849 - 7851.

Aducci P., Marra M., Fogliano V. and Fullone M. R. (1995). Fusicoccin receptors: perception and transduction of the fusicoccin signal. *Journal of Experimental Botany* 46: 1463 - 1478.

Aitken A. (1996). 14-3-3 and its possible role in co-ordinating multiple signal pathways. *Trends in Cell Biology* 6: 341 - 347.

Alder E. (1977). Lignin chemistry - past, present and future. *Wood Science Technology* 11: 169 - 217.

Ames B. N. (1966). Assay of inorganic phosphate, total phosphate, and phosphatases. *Methods in Enzymology* 8: 115 - 118.

Andrejaukas E., Hertel R. and Marmes D. (1985). Specific binding of the calcium antagonist [<sup>3</sup>H] verapamil to membrane fractions from plants. *The Journal of Biological Chemistry* 260: 5411 - 5414.

Assmann S. M., Simoncini L. and Schroeder J. I. (1985). Blue light activates electrogenic ion pumping in guard cell protoplasts of *Vicia faba*. *Nature* 318: 285 - 287.

Ayala F., O'Leary J. W. and Schumaker K. S. (1996). Increased vacuolar and plasma membrane H<sup>+</sup>-ATPase activities in *Salicornia bigelovii* Torr. in response to NaCl. *Journal of Experimental Botany* 47: 25 - 32.

Bachmann M., Huber J. L., Liao P. C., Gage D. A. and Huber S. C. (1996). The inhibitor protein of phosphorylated nitrate reductase from spinach (*Spinacea oleracea*) leaves is a 14-3-3 protein. *FEBS Letters* 387: 127 - 131.

Bacon J. S. D., MacDonald I. R. and Knight A. H. (1965). The development of invertase activity in slices of the root of *Beta vulgaris* L. washed under aseptic conditions. *The Biochemical Journal* 94: 175 - 182.

Baldwin J. E. and Krebs H. (1981). The evolution of metabolic cycles. *Nature* 291: 381 - 382.

Ball J. H., Williams L. and Hall J. L. (1987). Effect of SW26 and erythrosin B on ATPase activity and related processes in *Ricinus* cotyledons and cucumber hypocotyls. *Plant Science* 52: 11 - 15.



- Ballesteros E., Blumwald E., Donaire J. P. and Belver A. (1997). Na<sup>+</sup>/H<sup>+</sup> antiport activity in tonoplast vesicles isolated from sunflower roots induced by NaCl stress. *Physiologia Plantarum* 99: 328 - 334.
- Balling A. and Zimmermann U. (1990). Comparative measurements of the xylem pressure of *Nicotiana* plants by means of the pressure bomb and pressure probe. *Planta* 182: 325 - 338.
- Balling A., Zimmermann U. and Büchner K. H. (1988). Direct measurement of negative pressure in artificial-biological systems. *Naturwissenschaften* 75: 409 - 411.
- Ballio A., Chain E. B., De Leo P., Erlanger B. F., Mauri M., and Tonolo A. (1964). Fusicoccin: a new wilting toxin produced by *Fusicoccum amygdali* Del. *Nature* 203: 297.
- Barkla B. J., Zingarelli L., Blumwald E. and Smith A. (1995). Tonoplast Na<sup>+</sup>/K<sup>+</sup> antiport activity and its energization by the vacuolar H<sup>+</sup> - ATPase in the halophytic plant *Mesembryanthemum crystallinum* L. *Plant Physiology* 109: 549 - 556.
- Barry P. H. and Diamond J. M. (1984). Effects of unstirred layers on membrane phenomena. *Physiological Reviews* 64: 763 - 872.
- Bates N. J. (1998). The distribution and mobilisation of sulphur and nitrogen in leaves of *Triticum aestivum* approaching senescence. PhD Thesis. University of Wales Bangor, UK.
- Bayley S. T. and Kushner D. J. (1964). The ribosomes of the extremely halophytic bacterium, *Halobacterium cutirubrum*. *Journal of Molecular Biology* 9: 654 - 669.
- Beffagna N. and Romani G. (1988). Effects of two plasmalemma ATPase inhibitors on H<sup>+</sup> extrusion and intracellular pH in *Elodea densa* leaves. *Journal of Experimental Botany* 39: 1033 - 1043.
- Beffagna N. and Romani G. (1991). Modulation of the plasmalemma proton pump activity by intracellular pH in *Elodea densa* leaves: correlation between acid load and H<sup>+</sup> pumping activity. *Plant Physiology and Biochemistry* 29: 471 - 480.
- Behl R. and Raschke K. (1987). Close coupling between extrusion of H<sup>+</sup> and uptake of K<sup>+</sup> by barley roots. *Planta* 172: 531 - 538.
- Bell C. I. and Leigh R. A. (1996). Differential effects of turgor on sucrose and potassium transport at the tonoplast and the plasma membrane of sugar beet storage tissue. *Plant, Cell and Environment* 19: 191 - 200.
- Bellando M., Marré M. T., Sacco S., Talarico A., Venegoni A. and Marré E. (1995). Transmembrane potential-mediated coupling between H<sup>+</sup> pump operation and K<sup>+</sup> fluxes in *Elodea densa* leaves hyperpolarised by fusicoccin, light or acid load. *Plant, Cell and Environment* 18: 963 - 976.



Benkert R., Balling A. and Zimmermann U. (1991). Direct measurements of the pressure and flow in the xylem vessels of *Nicotiana tabacum* and their dependence on flow resistance and transpiration rate. *Botanica Acta* 104: 423 - 432.

Benkert R., Zhu J. J., Zimmermann G., Türk R., Bentrup F. W. and Zimmermann U. (1995). Long-term xylem pressure measurements in the liana *Tetrastigma voinierianum* by means of the xylem pressure probe. *Planta* 196: 804 - 813.

Bisson M. A. and Gutknecht J. (1975). Osmotic regulation in the marine alga *Codium decorticans*. I. Regulation of turgor by control of ionic composition. *Journal of Membrane Biology* 24: 183 - 200.

Bisson M. A. and Gutknecht J. (1980). Osmotic regulation in algae. In: *Plant Membrane Transport: Current Conceptual Issues* (edited by R. M. Spanswick, W. J. Lucas and J. Dainty). Elsevier/North-Holland Biomedical Press. ISBN 0-444-80192-8 pp. 131 - 146.

Bisson M. A., Kiegle E., Black D., Kiyosawa K. and Gerber N. (1995). The role of calcium in turgor regulation in *Chara longifolia*. *Plant, Cell and Environment* 18: 129 - 137.

Black R. F. (1956). Effect of NaCl in water culture on the ion uptake and growth of *Atriplex hastata* L. *Australian Journal of Biological Science* 9: 67 - 80.

Blumwald E. and Poole R. J. (1985). Na<sup>+</sup>/H<sup>+</sup> antiport in isolated tonoplast vesicles from storage tissue of *Beta vulgaris*. *Plant Physiology* 78: 163 - 167.

Boston P. F., Jackson P., Kynoch P. A. M. and Thompson R. J. (1982 {a}). Purification, properties, and immunohistochemical localization of human brain 14-3-3 protein. *Journal of Neurochemistry* 38: 1466 - 1474.

Boston P. F., Jackson P. and Thompson R. J. (1982 {b}). Human 14-3-3 protein radioimmunoassay, tissue distribution, and cerebrospinal fluid levels in patients with neurological disorders. *Journal of Neurochemistry* 38: 1475 - 1482.

Bowles D. J. (1990). Defence-related proteins in higher plants. *Annual Review of Biochemistry* 59: 873 - 907.

Bowling D. J. F. (1987). Measurement of the apoplastic activity of K<sup>+</sup> and Cl<sup>-</sup> in the leaf epidermis of *Commelina communis* in relation to stomatal activity. *Journal of Experimental Botany* 38: 1351 - 1355.

Boyer J. S. and Knipling E. B. (1965). Isopiestic technique for measuring leaf water potentials with a thermocouple psychrometer. *Proceedings of the National Academy of Sciences in the USA* 54: 1044 - 1051.

Boyer P. (1989). A perspective of the binding change mechanism for ATP synthesis. *The FASEB Journal* 3: 2164 - 2178.



- Braam J.** (1992). Regulated expression of the calmodulin-related TCH genes in cultures *Arabidopsis* cells: induction by calcium and heat shock. *Proceedings of the National Academy of Sciences in the USA* 89: 3213 - 3216.
- Brady C. J., Gibson T. S., Barlow E. W. R., Speirs J. and Wyn Jones R. G.** (1984). Salt-tolerance in plants. 1. Ions, compatible organic solutes and the stability of plant ribosomes. *Plant, Cell and Environment* 7: 571 - 578.
- Brandt J., Thordal-Christensen H., Vad K., Gregersen P. L. and Collinge D. B.** (1992). A pathogen-induced gene of barley encodes a protein showing high similarity to a protein kinase regulator. *The Plant Journal* 2: 815 - 820.
- Braun Y., Hassidim M., Lerner H. R. and Reinhold L.** (1986). Studies on H<sup>+</sup>-translocating ATPases in plants of varying resistance to salinity. *Plant Physiology* 81: 1050 - 1056.
- Briskin D. P.** (1990). The plasma membrane H<sup>+</sup>-ATPase of higher plant cells: biochemistry and transport function. *Archives of Biochemistry and Biophysics* 1019: 95 - 109.
- Briskin D. P. and Gawienowski M. C.** (1996). Role of the plasma membrane H<sup>+</sup>-ATPase in K<sup>+</sup> transport. *Plant Physiology* 111: 1199 - 1207.
- Briskin D. P. and Hanson J. B.** (1992). How does the plant plasma membrane H<sup>+</sup>-ATPase pump protons? *Journal of Experimental Botany* 43: 269 - 289.
- Brown R. M., Saxena I. M. and Kudlicka K.** (1996). Cellulose biosynthesis in higher plants. *Trends in Plant Science* 1: 149 - 155.
- Brummell D. A. and Hall J. L.** (1987). Rapid cellular responses to auxin and the regulation of growth. *Plant, Cell and Environment* 10: 523 - 543.
- Bush D. S.** (1993). Regulation of cytosolic calcium in plants. *Plant Physiology* 103: 7 - 13.
- Bush D. S.** (1995). Calcium regulation in plant cells and its role in signalling. *Annual Review of Plant Physiology and Plant Molecular Biology* 46: 95 - 122.
- Butcher R. W.** (1961). *A New Illustrated British Flora* (Part 1; *Lycopodiaceae* to *Salicaceae*). Leonard Hill Ltd. Eden Street, London, UK.
- Campbell W. H.** (1996). Nitrate reductase biochemistry comes of age. *Plant Physiology* 111: 355 - 361.
- Canny M. J.** (1995). A new theory for the ascent of sap - cohesion supported by tissue pressure. *Annals of Botany* 75: 343 - 375.



- Carpita N. C. and Gibeaut D. M. (1993). Structural models of primary cell walls in flowering plants: consistency of molecular structure with the physical properties of the walls during growth. *The Plant Journal* 3: 1 - 30.
- Cassab G. I. (1998). Plant cell wall proteins. *Annual Review of Plant Physiology and Plant Molecular Biology* 49: 281 - 309.
- Cassab G. I. and Varner J. E. (1988). Cell wall proteins. *Annual Review of Plant Physiology and Plant Molecular Biology* 39: 321 - 353.
- Chae Q., Park H. J. and Hong S. D. (1990). Loading of quin2 into the oat protoplast and measurement of cytosolic calcium ion concentration changes by phytochrome action. *Biochimica et Biophysica Acta* 1051: 115 - 122.
- Chan S. I. and Li P. M. (1990). Cytochrome c oxidase: understanding nature's design of a proton pump. *Biochemistry* 29: 1 - 12.
- Chapman V. J. (1947). *Suaeda maritima* (L.) Dum. *Journal of Ecology* 35: 293 - 302.
- Chazen O. and Neumann P. M. (1994). Hydraulic signals from the roots and rapid cell-wall hardening in growing maize (*Zea mays* L.) leaves are primary responses to polyethylene glycol-induced water deficits. *Plant Physiology* 104: 1385 - 1392.
- Chen Z., Fu H., Liu D., Chang P. L., Narasimhan M., Ferl R., Hasegawa P. M. and Bressan R. A. (1994). A NaCl-regulated plant gene encoding a brain protein homolog that activates ADP ribosyltransferase and inhibits protein kinase C. *The Plant Journal* 6: 729 - 740.
- Clapham A. R., Tutin T. G. and Moore D. M. (1987). *Flora of the British Isles* (3<sup>rd</sup> edition). Cambridge University Press, Cambridge, UK. ISBN 0-521-30985-9.
- Clapham A. R., Tutin T. G. and Warburg E. F. (1962). *Flora of the British Isles* (2<sup>nd</sup> edition). Cambridge University Press, Cambridge, UK.
- Clarkson D. T. (1993). Roots and the delivery of solutes to the xylem. *Philosophical Transactions of the Royal Society of London Series B* 341: 5 - 17.
- Cleland E. R. (1975). Auxin-induced hydrogen ion excretion: correlation with growth, and control by external pH and water stress. *Planta* 127: 233 - 242.
- Clipson N. J. W. (1987). Salt tolerance in the halophyte *Suaeda maritima* L. Dum. Growth, ion and water relations and gas exchange in response to altered salinity. *Journal of Experimental Botany* 38: 1996 - 2004.
- Clipson N. J. W., Tomos A. D., Flowers T. J. and Wyn Jones R. G. (1985). Salt tolerance in the halophyte *Suaeda maritima* L. Dum. The maintenance of turgor pressure and water-potential gradients in plants growing at different salinities. *Planta* 165: 392 - 396.



Cocucci M. C. (1986). Inhibition of plasma membrane and tonoplast ATPases by erythrosin B. *Plant Science* 47: 21 - 27.

Cocucci M. C. and Marré E. (1986). Erythrosin B as an effective inhibitor of electrogenic H<sup>+</sup> extrusion. *Plant, Cell and Environment* 9: 677 - 679.

Conner A. J. and Falloon P. G. (1993). Osmotic versus nutritional effects when rooting *in vitro* asparagus minicrowns on high sucrose media. *Plant Science* 89: 101 - 106.

Cosgrove D. J. (1993). How do plant cell walls extend? *Plant Physiology* 102: 1 - 6.

Cosgrove D. J. (1997). Assembly and enlargement of the primary cell wall in plants. *Annual Review of Cell Development and Biology* 13: 171 - 201.

Cosgrove D. J. and Hedrich R. (1991). Stretch-activated chloride, potassium, and calcium channels coexisting in plasma membranes of guard cells of *Vicia faba* L. *Planta* 186: 143 - 153.

Coster H. G. L., Steudle E. and Zimmermann U. (1976). Turgor pressure sensing mechanism. *Plant Physiology* 58: 636 - 643.

Coster H. G. L. and Zimmermann U. (1975). Transduction of turgor pressure by cell membrane compression. *Z. Naturforsch* 31: 46 - 563.

Cram W. J. (1976). Negative feedback regulation of transport in cells. The maintenance of turgor, volume and nutrient supply. In: *Encyclopaedia of Plant Physiology. New Series Volume 2. Transport in Plants II, Part A Cells* (edited by U. Lüttge and M. G. Pitman). Springer-Verlag Berlin, Heidelberg, New York. pp 284 - 316.

Cram W. J. (1980). A common feature of the uptake of solutes by root parenchyma cells. *Australian Journal of Plant Physiology* 7: 41 - 50.

Cram W. J. (1984). Mannitol transport and suitability as an osmoticum in root cells. *Physiologia Plantarum* 61: 396 - 404.

Csonka L. N. (1989). Physiological and genetic responses of bacteria to osmotic stress. *Microbiological Reviews* 53: 121 - 147.

Csonka L. N. and Hanson A. D. (1991). Prokaryotic osmoregulation: genetics and physiology. *Annual Review of Microbiology* 45: 569 - 606.

Cuin T. A. (1996). Effect of ozone-fumigation on single cell water and solute relations. PhD Thesis. University of Wales Bangor, UK.



- Curti G., Massardi F. and Lado P. (1993).** Synergistic activation of plasma membrane H<sup>+</sup>-ATPase in *Arabidopsis thaliana* cells by turgor decrease and by fusicoccin. *Physiologia Plantarum* 87: 592 - 600.
- Cutler D. F., Alvin K. L. and Price C. E. (1980).** *The Plant Cuticle*. Academic Press, New York.
- Dainty J. (1963).** Water relations of plant cells. *Advances in Botanical Research* 1: 279 - 326.
- Dainty J. (1985).** Water transport through the root. *Acta Horticulturae* 171: 21 - 31.
- Davenport J., Gruffydd Ll. D. and Beaumont A. R. (1975).** An apparatus to supply water of fluctuating salinity and its use in a study of the salinity tolerances of larvae of the scallop *Pecten maximus* L. *Journal of the Marine Biological Association UK*. 55: 391 - 409.
- De Michelis M. I., Rasi-Caldogno F., Pugliarello M. C. and Olivari C. (1996).** Fusicoccin binding to its plasma membrane receptor and the activation of the plasma membrane H<sup>+</sup>-ATPase. *Plant Physiology* 110: 957 - 964.
- De Boer B. (1997).** Fusicoccin - a key to multiple 14-3-3 locks? *Trends in Plant Science* 2: 60 - 66.
- De Jong A., Koerselman-Kooij J. W., Schuurmans J. A. M. J. and Borstlap A. C. (1996).** Characterization of the uptake of sucrose and glucose by isolated seed coat halves of developing pea seeds. Evidence that a sugar facilitator with diffusional kinetics is involved in seed coat unloading. *Planta* 199: 486 - 492.
- De Vetten N. C. and Ferl R. J. (1995).** Characterization of a maize G-box binding factor that is induced by hypoxia. *The Plant Journal* 7: 589 - 601.
- Delcour A. H., Martinac B., Adler J. and Kung C. (1989).** Modified reconstitution method used in patch-clamp studies of *Escherichia coli* ion channels. *The Biophysical Journal* 56: 631 - 636.
- Delrot S., Despeghel J. P. and Bonnemain J. L. (1980).** Phloem loading in *Vicia faba* leaves: effect of n-ethylmaleimide and parachloromercuribenzenesulfonic acid on H<sup>+</sup> extrusion, K<sup>+</sup> and sucrose uptake. *Planta* 149: 144 - 148.
- Dickerson R. E. (1972).** The structure and history of an ancient protein. *Scientific American* 226 (4): 58 - 72.
- Dickerson R. E. (1980).** Cytochrome c and the evolution of energy metabolism. *Scientific American* 242 (3): 98 - 111.
- Dickson D. M., Wyn Jones R. G. and Davenport J. (1980).** Steady state osmotic adaptation in *Ulva lactuca*. *Planta* 150: 158 - 165.



- Dickson D. M., Wyn Jones R. G. and Davenport J. (1982). Osmotic adaptation in *Ulva lactuca* under fluctuating salinity regimes. *Planta* 155: 409 - 415.
- Dixon H. H. and Joly J. (1894). On the ascent of sap. *Philosophical Transactions of the Royal Society of London* 57: 3 - 5.
- Dixon H. H. and Joly J. (1895). On the ascent of sap. *Philosophical Transactions of the Royal Society of London* 186: 563 - 576.
- Douglas P., Morrice N. and MacKintosh C. (1995). Identification of a regulatory phosphorylation site in the hinge 1 region of nitrate reductase from spinach (*Spinacea oleracea*) leaves. *FEBS Letters* 377: 58 - 65.
- Downton W. J. S. (1982). Growth and osmotic relations of the mangrove *Avicennia marina* as influenced by salinity. *Australian Journal of Biological Science* 9: 519 - 528.
- Edelmann H. G. (1995). Water potential modulates extensibility of rye coleoptile cell walls. *Botanica Acta* 108: 374 - 380.
- Ehwald R., Kowallick D., Meshcheryakov A. B and Kholodova V. P. (1980). Sucrose leakage from isolated parenchyma of sugar beet roots. *Journal of Experimental Botany* 31: 395 - 411.
- Epstein E. (1966). Dual pattern of ion absorption by plant cells and plants. *Nature* 212: 1324 - 1327.
- Epstein W. and Davies M. (1970). Potassium-dependent mutants of *Escherichia coli* K-12. *Journal of Bacteriology* 101: 836 - 843.
- Epstein W. and Schultz S. G. (1965). Cation transport in *Escherichia coli*. V. Regulation of cation content. *Journal of General Physiology* 49: 469 - 481.
- Epstein W, Walderhaug M. O., Polarek J. W., Hesse J. E., Dorus E. and Daniel J. M. (1990). The bacterial kdp K<sup>+</sup>-ATPase and its relation to other transport ATPases, such as the Na<sup>+</sup>/K<sup>+</sup> - and Ca<sup>2+</sup> -ATPases in higher organisms. *Philosophical Transactions of the Royal Society of London, Series B* 326: 479 - 487.
- Erikson O. F. and Moore B. W. (1980). Investigation of the axonal transport of three acidic soluble proteins (14-3-2, 14-3-3, and S100) in the rabbit visual system. *Journal of Neurochemistry* 35: 232 - 241.
- Falke L., Edwards K. L., Pickard B. G. and Misler S. A. (1988). A stretch-activated anion channel in tobacco protoplasts. *FEBS Letters* 237: 141 - 144.
- Farquar G. D. Dubbe D. R. and Raschke K. (1978). Gain of the feedback loop involving carbon dioxide and stomata: theory and measurement. *Plant Physiology* 62: 406 - 412.



- Feder N. and O'Brien T. P. (1968). Plant microtechniques: some principals and new methods. *American Journal of Botany* 55: 123 - 142.
- Felle H. H. (1988). Auxin causes oscillations of cytosolic free calcium and pH in *Zea mays* coleoptiles. *Planta* 176: 248 - 255.
- Felle H. H. (1998). The apoplastic pH of the *Zea mays* root cortex as measured with pH-sensitive microelectrodes: aspects of regulation. *Journal of Experimental Botany* 49: 987 - 995.
- Ferl R. J. (1996). 14-3-3 proteins and signal transduction. *Annual Review of Plant Physiology and Plant Molecular Biology* 47: 49 - 73.
- Field C. D. (1984 {a}). Ions in mangroves. In: *Physiology and Management of Mangroves* (edited by H. J. Teas). Dr W. Junk Publishers, The Hague. ISBN 90-6193-949-6. pp 43 - 48.
- Field C. D. (1984{b}). Movement of ions and water into the xylem sap of tropical mangroves. In: *Physiology and Management of Mangroves* (edited by H. J. Teas). Dr W. Junk Publishers, The Hague. ISBN 90-6193-949-6. pp 49 - 452.
- Fiscus E. L. (1977). Determination of hydraulic and osmotic properties of soybean root systems. *Plant Physiology* 59: 1013 - 1020.
- Flowers T. J. (1971). Salt tolerance in *Suaeda maritima* (L.) Dum. *Journal of Experimental Botany* 23: 310 - 321.
- Flowers T. J. (1972 {a}). Salt tolerance in *Suaeda maritima* (L.) Dum. The effect of sodium chloride on growth, respiration, and soluble enzymes in a comparative study with *Pisum sativum* L. *Journal of Experimental Botany* 23: 310 - 321.
- Flowers T. J. (1972 {b}). The effect of sodium chloride on enzyme activities from four halophyte species of *Chenopodiaceae*. *Phytochemistry* 11: 1881 - 1886.
- Flowers T. J. (1975). Halophytes. In: *Ion Transport in Plant Cells and Tissues* (edited by D. A. Baker and J. L. Hall). North-Holland Publishing Company. ISBN 0-7204-4519-1. pp 309 - 334.
- Flowers T. J. (1985). Physiology of halophytes. *Plant and Soil* 89: 41 - 56.
- Flowers T. J., Hajibagheri M. A. and Yeo A. R. (1991). Ion accumulation in the cell walls of rice plants growing under saline conditions: evidence for the Oertli hypothesis. *Plant, Cell and Environment* 14: 319 - 325.
- Flowers T. J., Hall J. L. and Ward M. E. (1976). Salt tolerance in the halophyte *Suaeda maritima*: some properties of malate dehydrogenase. *Philosophical Transactions of the Royal Society of London, Series B* 274: 523.



Flowers T. J., Troke P. F. and Yeo A. R. (1977). The mechanism of salt tolerance in halophytes. *Annual Review of Plant Physiology* 28: 89 - 121.

Flowers T. J. and Yeo A. R. (1988). Ion relations of salt tolerance. In: *Solute Transport in Plant Cells and Tissues* (edited by D. A. Baker and J. L. Hall). Longman Scientific and Technical, Harlow, UK. pp 392 - 416.

Freudenberg K. (1965). Lignin: its constitution and formation from p-hydroxycinnamyl alcohols. *Science* 148: 595 - 600.

Fricke W., Leigh R. A. and Tomos A. D. (1994). Epidermal solute concentrations and osmolality in barley leaves studied at single cell level. Changes along the leaf blade during leaf ageing and NaCl stress. *Planta* 192: 317 - 323.

Fry S. C. (1989). The structure and function of xyloglucan. *Journal of Experimental Botany* 40: 1 - 12.

Fry S. C. (1995). Polysaccharide-modifying enzymes in the plant cell wall. *Annual Review of Plant Physiology and Plant Molecular Biology* 46: 497 - 520.

Garbarino J. and DuPont F. M. (1988). NaCl induces a Na<sup>+</sup>/H<sup>+</sup> antiport in tonoplast vesicles from barley roots. *Plant Physiology* 86: 231 - 236.

Giaquinta R. T. (1976). Evidence for phloem loading from the apoplast. Chemical modification of membrane sulfhydryl groups. *Plant Physiology* 57: 872 - 875.

Giaquinta R. T. (1977). Phloem loading of sucrose. pH dependence and selectivity. *Plant Physiology* 59: 750 - 755.

Giaquinta R. T. (1979). Phloem loading of sucrose. Involvement of membrane ATPase and proton transport. *Plant Physiology* 63: 744 - 748.

Giaquinta R. T. (1983). Phloem loading of sucrose. *Annual Review of Plant Physiology* 34: 347 - 387.

Gifford E. M. and Foster A. S. (1989). *Morphology and Evolution of Vascular Plants (3<sup>rd</sup> edition)*. W. H. Freeman and Company, New York. ISBN 0-7167-1946-0.

Gilroy S. and Jones R. L. (1992). Gibberellic acid and abscisic acid co-ordinately regulate cytoplasmic calcium and secretory activity in barley aleurone protoplasts. *Proceedings of the National Academy of Sciences in the USA* 89: 3591 - 3595.

Gilroy S., Read N. D. and Trewavas A. J. (1990). Elevation of cytoplasmic calcium by caged calcium or caged inositol triphosphate initiates stomatal closure. *Nature* 346: 769 - 771.



- Gimmler H. (1988). Erythrosine B - a specific inhibitor of plasmalemma ATPase in intact microalgae? *Journal of Plant Physiology* 132: 545 - 551.
- Glenn E., Pfister R., Brown J. J., Thompson T. L. and O'Leary J. (1996). Na and K accumulation and salt tolerance of *Atriplex canescens* (Chenopodiaceae) genotypes. *American Journal of Botany* 83: 997 - 1005.
- Goldsmith M. H. M. (1977). The polar transport of auxin. *Annual Review of Plant Physiology* 28: 439 - 478.
- Gorham J., McDonnell E., Budrewicz E. and Wyn Jones R. G. (1985). Salt tolerance in the *Triticeae*: growth and solute accumulation in leaves of *Thinopyrum bessarabicum*. *Journal of Experimental Botany* 36: 1021 - 1031.
- Gorham J. and Wyn Jones R. G. (1983). Solute distribution in *Suaeda maritima*. *Planta* 157: 344 - 349.
- Gould J. M. (1983). Probing the structure and dynamics of lignin *in situ*. *What's New in Plant Physiology* 14: 5 - 8.
- Graves J. S. and Gutknecht J. (1976). Ion transport studies and determination of the cell wall elastic modulus in the marine alga, *Halicystis parvula*. *Journal of General Physiology* 67: 579 - 596.
- Graziana A., Fosset M., Ranjeva R., Hetherington A. M. and Lazdunski M. (1988).  $Ca^{2+}$  channel inhibitors that bind to plant cell membranes block  $Ca^{2+}$  entry into protoplasts. *Biochemistry* 27: 764 - 768.
- Greenway H. and Munns R. (1980). Mechanisms of salt tolerance in nonhalophytes. *Annual Review of Plant Physiology* 31: 149 - 190.
- Greenway H. and Munns R. (1983). Interactions between growth, uptake of  $Cl^-$  and  $Na^+$ , and water relations of plants in saline environments. II. Highly vacuolated cells. *Plant, Cell and Environment* 6: 575 - 590.
- Greenway H. and Osmond C. B. (1972). Salt responses of enzymes from species differing in salt tolerance. *Plant Physiology* 49: 256 - 259.
- Gustin M. C., Zhou X. L., Martinac B. and Kung C. (1988). A mechanosensitive ion channel in the yeast plasma membrane. *Science* 242: 762.
- Gutknecht J. (1968). Salt transport in *Valonia*: inhibition of potassium uptake by small hydrostatic pressures. *Science* 160: 68 - 70.
- Gutknecht J., Hastings D. F. and Bisson M. A. (1978). Ion transport and turgor pressure regulation in giant algal cells. In: *Membrane Transport in Biology, Volume 3* (edited by G. Giebisch, D. C. Tosteson and H. H. Ussing). Springer-Verlag, Berlin, Heidelberg, New York. pp. 125 - 174.



- Hahn S. H. and Saunders M. J. (1991). Cytokinin increases intracellular  $\text{Ca}^{2+}$  in *Funaria*: detection with indo-1. *Cell Calcium* 12: 675 - 681.
- Hall J. L. and Flowers T. J. (1973). The effect of salt on protein synthesis in the halophyte *Suaeda maritima*. *Planta* 110: 361 - 368.
- Halliday D., Resnick R. and Walker J. (1993). *Fundamentals of Physics (4<sup>th</sup> Edition)*. John Wiley and Sons Inc., New York, Chichester, Brisbane, Toronto, Singapore. ISBN 0-471-60012-1. pp 443 - 474.
- Hanson J. B. and Trewavas A. J. (1982). Regulation of plant cell growth: the changing perspective. *New Phytologist* 90: 1 - 18.
- Harvey D. M. R., Flowers T. J. and Hall J. L. (1976). Localization of chloride in leaf cells of the halophyte *Suaeda maritima* by silver precipitation. *New Phytologist* 77: 319 - 323.
- Harvey H. J., Venis M. A. and Trewavas A. J. (1989). Partial purification of a protein from maize (*Zea mays*) coleoptile membranes binding the  $\text{Ca}^{2+}$  -channel antagonist, verapamil. *Biochemical Journal* 257: 95 - 100.
- Hassidim M., Braun Y., Lerner H. R. and Reinhold L. (1990).  $\text{Na}^+/\text{H}^+$  and  $\text{K}^+/\text{H}^+$  antiport in root membrane vesicles isolated from the halophyte *Atriplex* and the glycophyte cotton. *Plant Physiology* 94: 1795 - 1801.
- Hastings D. F. and Gutknecht J. (1974). Turgor pressure regulation: modulation of active potassium transport by hydrostatic pressure gradients. In: *Membrane Transport in Plants* (edited by U. Zimmermann and J. Dainty). Springer-Verlag, Berlin, Heidelberg, New York. ISBN 3-540-06989-5. pp 79 - 83.
- Hedrich R., Barbier-Brygoo H., Felle H., Flügge U. I., Lüttge U., Maathuis F. J. M., Marx S., Prins H. B. A., Raschke K., Schnabl H., Schroder J. I., Struve I., Taize L. and Ziegler P. (1988). General mechanisms for solute transport across the tonoplast of plant vacuoles: a patch clamp survey of ion channels and proton pumps. *Botanica Acta* 101: 7 - 13.
- Hedrich R. and Schroeder J. I. (1989). The physiology of ion channels and electrogenic pumps in higher plants. *Annual Review of Plant Physiology* 40: 539 - 569.
- Hellebust J. A. (1976). Osmoregulation. *Annual Review of Plant Physiology* 27: 485 - 505.
- Henriksen G. H., Raman D. R., Walker L. P. and Spanswick R. M. (1992). Measurement of net fluxes of ammonium and nitrate at the surface of barley roots using ion-selective microelectrodes. II. Patterns of uptake along the root axis and evaluation of the microelectrode flux estimation technique. *Plant Physiology* 99: 734 - 747.



Hetherington A. M. and Trewavas A. J. (1984). Binding of nitrendipine, a calcium channel blocker, to pea shoot membranes. *Plant Science Letters* 35: 109 - 113.

Hewitt E. J. (1966). *Sand and water culture methods used in the study of plant nutrition* (revised 2<sup>nd</sup> edition). Commonwealth Agricultural Bureau, Farnham Royal, Bucks., England, UK. pp 547.

Hüsken D., Steudle E. and Zimmermann U. (1978). Pressure probe technique for measuring water relations of cells in higher plants. *Plant Physiology* 61: 158 - 163.

Hinde P. (1994). The role of potassium as an osmoticum in barley leaf cells. PhD Thesis. University of Wales Bangor, UK.

Hinde P., Richardson P., Koyro H. W. and Tomos A. D. (1998). Quantitative X-ray microanalysis of solutes in individual plant cells: a comparison of microdroplet *in situ* frozen-hydrated data. *Journal of Microscopy* 191: 303 - 310.

Hinkle P. C. and McCarty R. E. (1978). How cells make ATP. *Scientific American* 238 (3): 104 - 123.

Holloway P. J. (1980). Structure and histochemistry of plant cuticular membranes: an overview. In: *The Plant Cuticle* (edited by D. F. Cutler, K. L. Alvin and C. E. Price. Academic Press. New York. pp. 1 - 32.

Holloway P. J. (1983). Some variations in the composition of suberin from cork layers of higher plants. *Phytochemistry* 22: 495 - 502.

Hooke R. (1665). *Micrographia: or some physiological descriptions of minute bodies made by magnifying glasses*. Hardback: Science Heritage Ltd (1987), ISBN 0940095076. CD Rom: Octavo Corporation (1998), ISBN 1891788027.

Husted S. and Schjoerring J. K. (1995). Apoplastic pH and Ammonium concentration in leaves of *Brassica napus* L. *Plant Physiology* 109: 1453 - 1460.

Ichimura T., Isobe T., Okuyama T., Takahashi N., Araki K., Kuwano R. and Takahashi Y. (1988). Molecular cloning of cDNA coding for brain-specific 14-3-3 protein, a protein kinase-dependent activator of tyrosine and tryptophan hydroxylases. *Proceedings of the National Academy of Sciences in the USA* 85: 7084 - 7088.

Ichimura T., Isobe T., Yamauchi T. and Fujisawa H. (1987). Brain 14-3-3 protein is an activator protein that activates tryptophan 5-monooxygenase in the presence of Ca<sup>2+</sup>, calmodulin-dependent protein kinase II. *FEBS Letters* 219: 79 - 82.

Ichimura T., Sugano H., Kuwano R., Sunaya T., Okuyama T. and Isobe T. (1991). Widespread distribution of the 14-3-3 protein in vertebrate brains and bovine tissues: correlation with the distribution of calcium-dependent protein kinases. *Journal of Neurochemistry* 56: 1449 - 1451.



Inesi G. (1985). Mechanism of calcium transport. *Annual Review of Physiology* 47: 573 - 601.

Ingram J. and Bartels D. (1996). The molecular basis of dehydration tolerance in plants. *Annual Review of Plant Physiology and Plant Molecular Biology* 47: 377 - 403.

Jachetta J. J., Appelby A. P. and Boersma L. (1986). Use of the pressure vessel to measure concentrations of solutes in apoplastic and membrane-filtered symplastic sap in sunflower leaves. *Plant Physiology* 82: 995 - 999.

Jahn T., Fuglsang A. T., Olsson A., Brüntrup I. M., Collinge D. B., Volkmann D., Sommarin M., Palmgren M. G. and Larsson C. (1997). The 14-3-3 protein interacts directly with the C-terminal region of the plant plasma membrane H<sup>+</sup>-ATPase. *The Plant Cell* 9: 1805 - 1814.

Jahn T., Johansson F., Lüthen H., Volkmann D. and Larsson C. (1996). Reinvestigation of auxin and fusicoccin stimulation of the plasma membrane H<sup>+</sup>-ATPase activity. *Planta* 199: 359 - 365.

Jarillo J. A., Capel J., Leyva A., Martinez-Zapater J. M. and Salinas J. (1994). Two related low-temperature-inducible genes of *Arabidopsis* encode proteins showing high homology to 14-3-3 proteins, a family of putative kinase regulators. *Plant Molecular Biology* 25: 693 - 704.

Jefferies R. L., Jensen A. and Bazoly D. (1983). The biology of the annual *Salicornia europaea* agg. at the limits of its range in Hudson Bay. *Canadian Journal of Botany* 61: 762 - 773.

Johansson F., Sommarin M. and Larsson C. (1993). Fusicoccin activates the plasma membrane H<sup>+</sup>-ATPase by a mechanism involving the C-terminal inhibitory domain. *Plant Cell* 5: 321 - 327.

Jose M. and Puigdomenech P. (1993). Structure and expression of genes coding for structural proteins of the plant cell wall. *New Phytologist* 125: 259 - 282.

Juniper B. E. and Jeffree C. E. (1982). *Plant Surfaces*. Edward Arnold, London.

Katz A., Pick U. and Avron M. (1992). Modulation of Na<sup>+</sup>/K<sup>+</sup> antiporter activity by extreme pH and salt in the halotolerant alga *Dunaliella salina*. *Plant Physiology* 100: 1224 - 1229.

Kauss H. (1977). Biochemistry of osmotic regulation. *International Review of Biochemistry. Plant Biochemistry II* (edited by D. H. Northcote) 13: 119 - 140.

Kidou S., Umeda M., Kato A. and Uchimiya H. (1993). Isolation and characterization of a rice cDNA similar to the bovine brain-specific 14-3-3 protein gene. *Plant Molecular Biology* 21: 191 - 194.



- Kim J. B. and Carpita N. C. (1992).** Changes in esterification of the uronic acid groups of cell wall polysaccharides during elongation of maize coleoptiles. *Plant Physiology* 98: 646 - 653.
- Kinraide T. B. and Etherton B. (1980).** Electrical evidence for different mechanisms of uptake for basic, neutral, and acidic amino acids in oat coleoptiles. *Plant Physiology* 65: 1085 - 1089.
- Kinraide T. B. and Wyse R. E. (1986).** Electrical evidence for turgor inhibition of proton extrusion in sugar beet taproot. *Plant Physiology* 82: 1148 - 1150.
- Kirk T. K. (1971).** Effects of microorganisms on lignin. *Annual Review of Phytopathology* 9: 185 - 210.
- Kirst G. O. and Bisson M. A. (1979).** Regulation of turgor pressure in marine algae: ions and low molecular weight organic compounds. *Australian Journal of Plant Physiology* 6: 539 - 556.
- Knight H., Trewavas A. J. and Knight M. R. (1997).** Calcium signalling in *Arabidopsis thaliana* responding to drought and salinity. *The Plant Journal* 12: 1067 - 1078.
- Knight M. R., Campbell A. K., Smith S. M. and Trewavas A. J. (1991).** Transgenic plant aequorin reports the effects of touch and cold-shock and elicitors on cytoplasmic calcium. *Nature* 352: 524 - 526.
- Kochian L. V., Shaff J. E. and Lucas W. J. (1989).** High affinity K<sup>+</sup> uptake in maize roots - a lack of coupling with H<sup>+</sup> efflux. *Plant Physiology* 91: 1202 - 1211.
- Kolattukudy P. E. (1980).** Biopolyester membranes of plants: cutin and suberin. *Annual Review of Plant Physiology* 32: 539 - 567.
- Kolattukudy P. E. (1987).** Lipid-derived defensive polymers and waxes and their role in plant microbe interaction. In: *The Metabolism, Structure and Function of Plant Lipids* (edited by P. K. Stumpf). Plenum Press, New York, London. pp. 291 - 314.
- Korthout H. A. A. J. and De Boer A. H. (1994).** A fusicoccin binding protein belongs to the family of 14-3-3 brain protein homologs. *The Plant Cell* 6: 1681 - 1692.
- Laimins L. A., Rhoads D. B., Altendorf K. and Epstein W. (1978).** Identification of the structural proteins of an ATP-driven potassium transport system in *Escherichia coli*. *Proceedings of the National Academy of Sciences in the USA* 75: 3216 - 3219.
- Laimins L. A., Rhoads D. B. and Epstein W. (1981).** Osmotic control of kdp operon expression in *Escherichia coli*. *Proceedings of the National Academy of Sciences in the USA* 78: 464 - 468.



Lanfermeijer F. C. and Prins H. B. A. (1994). Modulation of H<sup>+</sup>-ATPase activity by fusicoccin in plasma membrane vesicles from oat (*Avena sativa* L.) roots. *Plant Physiology* 104: 1277 - 1285.

Larsen H. (1967). Biochemical aspects of extreme halophilism. In: *Advances in Microbial Physiology Volume 1* (edited by A. H. Rose and J. F. Wilkinson). Academic Press, London, New York. pp 97 - 132.

Larsson C., Sommarin M. and Widell S. (1994). Isolation of highly purified plasma membranes and the separation of inside-out and right-side-out vesicles. *Methods in Enzymology* 228: 451 - 469.

Lee Y. and Satter R. L. (1989). Effects of white, blue, red light and darkness on pH of the apoplast in the *Samanea pulvinus*. *Planta* 178: 31 - 40.

Leigh R. A., Ap Rees T., Fuller W. A. and Banfield J. (1979). The location of acid invertase activity and sucrose in the vacuoles of storage roots of beetroot (*Beta vulgaris*). *Biochemical Journal* 178: 539 - 547.

Leigh R. A. and Tomos A. D. (1983). An attempt to use isolated vacuoles to determine the distribution of sodium and potassium in cells of storage roots of red beet (*Beta vulgaris* L.). *Planta* 159: 469 - 475.

Leigh R. A. and Wyn Jones R. G. (1984). A hypothesis relating critical potassium concentrations for growth to the distribution and functions of this ion in the plant cell. *New Phytologist* 97: 1 - 13.

Leonard R. T. (1982). The plasma membrane ATPase of plant cells: cation or proton pump? In: *Membranes and Transport, Volume 2* (edited by A. N. Martinosi). Plenum, New York. pp. 633 - 637.

Lüthen H., Bigdon M. and Bottger M. (1990). Reexamination of the acid growth theory of auxin action. *Plant Physiology* 93: 931 - 939.

Lüttge U., Kluge M. and Ball E. (1975). Effects of osmotic gradients on vacuolar malic acid storage. A basic principle in oscillatory behaviour of crassulacean acid metabolism. *Plant Physiology* 56: 613 - 616.

Lowen C. Z. and Satter R. L. (1989). Light-promoted changes in apoplastic K<sup>+</sup> activity in the *Samanea saman* pulvinus, monitored with liquid membrane micro-electrodes. *Planta* 179: 421 - 427.

Lowry O. H. and Passioneau J. V. (1972). *A flexible system of enzymatic analysis*. Academic Press, New York, USA.

Maathuis F. J. M., Flowers T. J. and Yeo A. R. (1992). Sodium chloride compartmentation in leaf vacuoles of the halophyte *Suaeda maritima* (L.) Dum. and its relation to tonoplast permeability. *Journal of Experimental Botany* 43: 1219 - 1223.



- Maathuis F. J. M. and Prins H. B. A. (1990). Patch clamp studies on root cell vacuoles of a salt-tolerant and a salt-sensitive *Plantago* species. *Plant Physiology* 92: 23 - 28.
- Maathuis F. J. M. and Sanders D. (1996). Mechanisms of potassium absorption by higher plant roots. *Physiologia Plantarum* 96: 158 - 168.
- Maathuis F. J. M. and Sanders D. (1997). Regulation of K<sup>+</sup> adsorption in plant root cells by external K<sup>+</sup>: interplay of different plasma membrane K<sup>+</sup> transporters. *Journal of Experimental Botany* 48: 451 - 458.
- Maathuis F. J. M., Sanders D. and Gradmann D. (1997). Kinetics of high-affinity K<sup>+</sup> uptake in plants, derived from K<sup>+</sup>-induced changes in current-voltage relationships. A modelling approach to the analysis of carrier-mediated transport. *Planta* 203: 229 - 236.
- MacRobbie E. A. C. (1988). Control of ion fluxes in stomatal guard cells. *Botanica Acta* 101: 140 - 148.
- Malone M. (1993). Hydraulic signals. *Philosophical Transactions of the Royal Society of London, Series B* 341: 33 - 39.
- Malone M., Leigh R. A. and Tomos A. D. (1989). Extraction and analysis of sap from individual wheat leaf cells: the effect of sampling speed on the osmotic pressure of extracted sap. *Plant, Cell and Environment* 12: 919 - 926.
- Malone M., Leigh R. A. and Tomos A. D. (1991). Concentrations of vacuolar inorganic ions in individual cells of intact wheat leaf epidermis. *Journal of Experimental Botany* 42: 305 - 309.
- Malone M. and Tomos A. D. (1992). Measurement of gradients of water potential in elongating pea stem by pressure probe and picolitre osmometry. *Journal of Experimental Botany* 43: 1325 - 1331.
- Mansfield T. A., Hetherington A. M. and Atkinson C. J. (1990). Some current aspects of stomatal physiology. *Annual Review of Plant Physiology and Plant Molecular Biology* 41: 55 - 75.
- Marra M., Ballio A., Fullone M. R. and Aducci P. (1992). Some properties of a functional reconstituted plasmalemma H<sup>+</sup>-ATPase activated by fusicoccin. *Plant Physiology* 98: 1029 - 1034.
- Marra M., Fullone R. F., Fogliano V., Pen J., Mattei M., Masi S and Aducci P. (1994). The 30-kilodalton protein present in purified fusicoccin receptor preparations is a 14-3-3-like protein. *Plant Physiology* 106: 1497 - 1501.
- Marré E. (1979). Fusicoccin: a tool in plant physiology. *Annual Review of Plant Physiology* 30: 273 - 288.



- Marré E., Lado P., Rasi-Caldogno F. and Colombo R. (1973). Correlation between cell enlargement in pea internode segments and decrease in the pH of the medium of incubation. I. Effects of fusicoocin, natural and synthetic auxins and mannitol. *Plant Science* 1: 179 - 184.
- Marschner H. (1995). *Mineral Nutrition in Higher Plants* (2<sup>nd</sup> edition). Academic Press Ltd., Cambridge, UK. ISBN 0-12-473543-6.
- Martinac B., Buechner M., Delcour A. H., Adler J. and Kung C. (1987). Pressure-sensitive ion channel in *Escherichia coli*. *Proceedings of the National Academy of Sciences in the USA* 84: 2297 - 2301.
- Marvier A. C., Williams L. E., Leigh R. A. and Hall J. L. (1997). Effects of prolonged washing on primary and secondary transport processes at the plasma membrane in red beet storage tissue. *Plant Physiology* 115: 263 - 272.
- Mauseth J. D. (1988). *Plant Anatomy*. The Benjamin/Cummings Publishing Company Inc, Wokingham, UK. ISBN 0-8053-4570-1.
- McArthur E. D. and Sanderson S. C. (1984). Distribution, systematics, and evolution of *Chenopodiaceae*: an overview. In: *Proceedings of the Symposium on the Biology of Atriplex and Related Chenopods, May 2 - 6, 1983, Provo, Utah* (edited by A. R. Tiedemann, E. D. McArthur, H. C. Stutz, K. R. Stevens and K. L. Johnson). USDA Forest Service, General Technical Report INT-172, Ogden, Utah, pp 14 - 24.
- McCann M. C. and Roberts K. (1994). Changes in cell wall architecture during cell elongation. *Journal of Experimental Botany* 45: 1683 - 1691.
- McCann M. C., Shi J., Roberts K. and Carpita N. C. (1994). Changes in pectin structure and localisation during the growth of unadapted and NaCl-adapted tobacco cells. *The Plant Journal* 5: 773 - 780.
- McCann M. C., Wells B. and Roberts K. (1990). Direct visualization of cross-links in the primary cell wall. *Journal of Cell Science* 96: 323 - 334.
- McLaggan D., Naprstek J., Buurman E. T. and Epstein W. (1994). Interdependence of K<sup>+</sup> and glutamate accumulation during osmotic adaptation of *Escherichia coli*. *The Journal of Biological Chemistry* 269: 1911 - 1917.
- McNeil M., Darvill A. G., Fry S. C. and Albersheim P. (1984). Structure and function of the primary cell wall of plants. *Annual Review of Biochemistry* 53: 625 - 663.
- Meidner H. and Edwards M. (1975). Direct measurements of turgor pressure potentials of guard cells. I. *Journal of Experimental Botany* 26: 319 - 330.
- Meidner H. and Sheriff D. W. (1976). *Water and Plants*. Blackie and Son Ltd., Glasgow. ISBN 0-216-90080-8.



- Meinzer F. C. and Moore P. H. (1988).** Effect of apoplastic solutes on water potential in elongating sugarcane leaves. *Plant Physiology* 86: 873 - 879.
- Meyer C., Feyerabend M. and Weiler E. W. (1989).** Fusicoccin-binding proteins in *Arabidopsis thaliana* (L.) Heynh. Characterization, solubilization, and photoaffinity labelling. *Plant Physiology* 89: 692 - 699.
- Michelet B. and Boutry M. (1995).** The plasma membrane H<sup>+</sup>-ATPase. A highly regulated enzyme with multiple physiological functions. *Plant Physiology* 108: 1 - 6.
- Miller R. J. and Freedman S. B. (1984).** Are dihydropyridine binding-sites voltage sensitive calcium channels. *Life Sciences* 34: 1205 - 1221.
- Milling R. J., Hall J. L. and Leigh R. A. (1993).** Purification of an acid invertase from washed discs of storage root of red beet (*Beta vulgaris* L.). *Journal of Experimental Botany* 44: 1679 - 1686.
- Mitchell P. (1979).** Keilin's respiratory chain concept and its chemiosmotic consequences. *Science* 206: 1148 - 1159.
- Moore B. W. and Perez V. J. (1967).** Specific acid proteins of the nervous system. In: *Physiological and Biochemical Aspects of Nervous Integration* (edited by F. D. Carlson). Prentice Hall Press, UK. pp. 343 - 359.
- Moorhead G., Douglas P., Morrice N., Scarabel M., Aitken A. and MacKintosh C. (1996).** Phosphorylated nitrate reductase from spinach leaves is inhibited by 14-3-3 proteins and activated by fusicoccin. *Current Biology* 6: 1104 - 1113.
- Morgan A. J. (1985).** X-ray microanalysis in electron microscopy for biologists, (Royal Microscopical Society Handbooks N° 05). Oxford University Press, Oxford, UK. ISBN 0-19-856409-0.
- Morris C. E. (1990).** Mechanosensitive ion channels. *Journal of Membrane Biology* 113: 93 - 107.
- Moustacas A. M., Nari J., Borel M., Noat G. and Ricard J. (1991).** Pectin methylesterase, metal ions and plant cell-wall extension. The role of metal ions in plant cell-wall extension. *The Biochemical Journal* 279: 351 - 354.
- Munns R. and Passioura J. B. (1984).** Hydraulic resistance of plants. III. Effects of NaCl in barley and lupins. *Australian Journal of Plant Physiology* 11: 351 - 359.
- Nayler W. G. and Horowitz J. D. (1983).** Calcium antagonists: a new class of drugs. *Pharmacology and Therapeutics* 20: 203 - 262.
- Newbold D. E. (1969).** *Late Seventeenth Century Scientists* (edited by D. Hutchings). Pergamon Press, Oxford, New York.



- Nicholls D. G. (1982). *Bioenergetics: an introduction to the chemiosmotic theory*. Academic Press, London, New York. ISBN 0-12-518122-1 pp. 110.
- Nicholls D. G. and Ferguson S. J. (1992). *Bioenergetics 2*. Academic Press, London, New York. ISBN 0-12-518124-8.
- Niu X., Bressan R. A., Hasegawa P. M. and Pardo J. M. (1995). Ion homeostasis in NaCl stress environments. *Plant Physiology* 109: 735 - 742.
- Nobel P. S. (1983). *Biophysical Plant Physiology and Ecology*. W. H. Freeman and Company, New York.
- Nobel P. S. (1991). *Physicochemical and Environmental Plant Physiology*. Academic Press Inc., London, UK. ISBN 0-12-520021-8.
- Nonami H. and Boyer J. S. (1987). Origin of growth-induced water potential. Solute concentration is low in apoplast of enlarging tissues. *Plant Physiology* 83: 596 - 601.
- Oertli J. J. (1968). Extracellular salt accumulation, a possible mechanism of salt injury in plants. *Agrochimica* 12: 461 - 469.
- Olivari C., Pugliarello M. C., Rasi-Caldogno F. and De Michelis. (1993). Characteristics and regulatory properties of the H<sup>+</sup>-ATPase in a plasma membrane fraction purified from *Arabidopsis thaliana*. *Botanica Acta* 106: 13 - 19.
- Outlaw W. H. (1983). Current concepts on the role of potassium in stomatal movements. *Physiologia Plantarum* 59: 302 - 311.
- O'Toole J. C. and Cruz T. T. (1979). Leaf rolling and transpiration. *Plant Science Letters* 16: 111 - 114.
- Passioura J. B. (1980). The meaning of the matric potential. *Journal of Experimental Botany* 31: 1161 - 1169.
- Passioura J. B. (1994). The physical chemistry of the primary cell wall: implications for the control of expansion rate. *Journal of Experimental Botany* 45: 1675 - 1682.
- Pedersen P. L. and Carafoli E. (1987). Ion motive ATPases. I. Ubiquity, properties, and significance to cell function. *Trends in Biochemical Science* 12: 146 - 150.
- Peng H. B. and Jaffe L. F. (1976). Cell-wall formation in *Pelvetia* embryos. A freeze fracture study. *Planta* 133: 57 - 71.
- Perry C. A., Leigh R. A., Tomos A. D., Wyse R. E. and Hall J. L. (1987). The regulation of turgor pressure during sucrose mobilisation and salt accumulation by excised storage-root tissue of red beet. *Planta*: 170: 353 - 361.



- Peterkin P. I. and Fitt P. S. (1971). Nucleic acid enzymology of extremely halophytic bacteria. *The Biochemical Journal* 121: 613 - 620.
- Pitman M. G. (1963). The determination of the salt relations of the cytoplasmic phase in cells of beetroot tissue. *Australian Journal of Biological Sciences* 16: 647 - 668.
- Pitman M. G. (1984). Transport across the root and shoot/root interactions. In: *Salinity Tolerance in Plants: Strategies for Crop Improvement* (edited by R. C. Staples and G. H. Toennissen). John Wiley and Sons Inc., New York. pp 93 - 123.
- Pitman M. G., Lüttge U., Lauchli A. and Ball E. (1974). Ion uptake to slices of barley leaves, and regulation of K content in cells of the leaves. *Zeitschrift für Pflanzenphysiologie* 72: 75 - 88.
- Pomper K. W. and Breen P. J. (1995). Levels of apoplastic solutes in developing strawberry fruit. *Journal of Experimental Botany* 46: 743 - 752.
- Poole R. J. (1976). Transport in cells of storage tissues. In: *Encyclopaedia of Plant Physiology, New series, Volume 2A: Transport II, Part A, Cells* (edited by U. Lüttge and M. G. Pitman). Springer-Verlag, Berlin, Heidelberg, New York. pp. 229 - 248.
- Poole R. J. (1978). Energy coupling for membrane transport. *Annual Review of Plant Physiology* 29: 437 - 460.
- Raschke K. (1970). Stomatal responses to pressure changes and interruptions in the water supply of detached leaves of *Zea mays* L. *Plant Physiology* 45: 415 - 423.
- Raschke K. (1979). Movements of stomata. In: *Encyclopaedia of Plant Physiology, New Series Volume 7: Physiology of Movements* (edited by W. Haupt and M. E. Feinleib). Springer-Verlag, Berlin, Heidelberg, New York. pp. 383 - 441.
- Rasi-Caldogno F., Carnelli A. and De Michelis M. I. (1995). Identification of the plasma membrane  $\text{Ca}^{2+}$ -ATPase and its autoinhibitory domain. *Plant Physiology* 108: 105 - 113.
- Rasi-Caldogno F., De Michelis M. I., Pugliarello M. C. and Marré E. (1986).  $\text{H}^+$ -pumping driven by the plasma membrane ATPase in membrane vesicles from radish. Stimulation by fusicoccin. *Plant Physiology* 82: 121 - 125.
- Rasi-Caldogno F. and Pugliarello M. C. (1985). Fusicoccin stimulates the  $\text{H}^+$ -ATPase of plasmalemma in isolated membrane vesicles from radish. *Biochemical and Biophysical Research Communication* 133: 280 - 285.
- Rasi-Caldogno F., Pugliarello M. C., Olivari C. and De Michelis M. I. (1993). Controlled proteolysis mimics the effect of fusicoccin on the plasma membrane  $\text{H}^+$ -ATPase. *Plant Physiology* 103: 391 - 398.



- Rausch T., Kirsch M., Low R., Lehr A., Viereck R and Zhigang A. (1996). Salt stress responses of higher plants: the role of proton pumps and Na<sup>+</sup>/H<sup>+</sup>-antiporters. *Journal of Plant Physiology* 148: 425 - 433.
- Rayle D. L. (1973). Auxin induced hydrogen-ion excretion in *Avena* coleoptiles and its implications. *Planta* 114: 63 - 73.
- Rayle D. L. and Cleland R. E. (1992). The acid growth theory of auxin-induced cell elongation is alive and well. *Plant Physiology* 99: 1271 - 1274.
- Rees D. A. (1977). *Polysaccharide Shapes*. Chapman and Hall, London.
- Reimann C. (1992). Sodium exclusion by *Chenopodium* species. *Journal of Experimental Botany* 43: 503 - 510.
- Reinhold L. and Kaplan A. (1984). Membrane transport of sugars and amino acids. *Annual Review of Plant Physiology* 35: 45 - 83.
- Reinhold L, Seiden A. and Volokita M. (1984). Is modulation of the rate of proton pumping a key event in osmoregulation? *Plant Physiology* 75: 846 - 849.
- Rengel Z. and Elliott D. C. (1992). Mechanisms of aluminium inhibition of net <sup>45</sup>Ca<sup>2+</sup> uptake by *Amaranthus* protoplasts. *Plant Physiology* 98: 632 - 638.
- Reuveni M., Bennett A. B., Bressan R. A. and Hasegawa P. M. (1990). Enhanced H<sup>+</sup> transport capacity and ATP hydrolysis activity of the tonoplast H<sup>+</sup>-ATPase after NaCl adaptation. *Plant Physiology* 94: 524 - 530.
- Reuveni M., Colombo R., Lerner H. R., Pradet A. and Poljakoff-Mayber A. (1987). Osmotically induced proton extrusion from carrot cells in suspension culture. *Plant Physiology* 85: 383 - 388.
- Rhoads D. B. and Epstein W. (1977). Energy coupling to net K<sup>+</sup> transport in *Escherichia coli* K-12. *The Journal of Biological Chemistry* 252: 1394 - 1401.
- Rhoads D. B., Laimins L. and Epstein W. (1978). Functional organization of the kdp genes of *Escherichia coli* K12. *Journal of Bacteriology* 135: 445 - 452.
- Rhoads D. B., Waters F. B. and Epstein W. (1976). Cation transport in *Escherichia coli*. VIII. Potassium transport mutants. *Journal of General Physiology* 67: 325 - 341.
- Richter C. and Dainty J. (1989). Ion behaviour in plant cell walls. I. Characterisation of the *Sphagnum russowii* cell wall ion exchanger. *Canadian Journal of Botany* 67: 451 - 459.
- Roberts K. (1990). Structures at the plant cell surface. *Current Opinions in Cell Biology* 2: 920 - 928.



- Robinson K., Jones D., Patel Y., Martin H., Madrazo J., Martin S., Howell S., Elmore M., Finnen M. J. and Aitken A. (1994). Mechanism of inhibition of protein kinase C by 14-3-3 isoforms. *The Biochemical Journal* 299: 853 - 861.
- Rothstein A. (1970). Sulfhydryl groups in membrane structure and function. *Current Topics in Membrane Transport* 1: 135 - 136.
- Russ U., Grolig F. and Wagner G. (1991). Changes of cytoplasmic free  $\text{Ca}^{2+}$  in the green alga *Mougeotia scalaris* as monitored with indo-1, and their effect on the velocity of chloroplast movement. *Planta* 184: 105 - 112.
- Rygel J., Prichard J., Zhu J. J., Tomos A. D. and Zimmermann U. (1993). Transpiration induces radial turgor pressure gradients in wheat and maize roots. *Plant Physiology* 103: 493 - 500.
- Rygel J. and Zimmermann U. (1990). Radial and axial turgor pressure measurements in individual root cells of *Mesembryanthemum crystallinum* grown under various saline conditions. *Plant, Cell and Environment* 13: 15 - 26.
- Saunders M. J. and Hepler P. K. (1982). Calcium ionophore - A23187 stimulates cytokinin-like mitosis in *Funaria*. *Science* 217: 943 - 945.
- Saunders M. J. and Hepler P. K. (1983). Calcium-antagonists and calmodulin inhibitors block cytokinin-induced bud formation in *Funaria*. *Developmental Biology* 99: 41 - 49.
- Schneider H., Wistuba N., Miller B., Geßner P., Thürmer F., Melcher P., Meinzer F. and Zimmermann U. (1997 {b}). Diurnal variation in the radial reflection coefficient of intact maize roots determined with the xylem pressure probe. *Journal of Experimental Botany* 48: 2045 - 2053.
- Schneider H., Zhu J. J. and Zimmermann U. (1997 {a}). Xylem and cell turgor pressure probe measurements in intact roots of glycophytes: transpiration induces a change in the radial and cellular reflection coefficients. *Plant, Cell and Environment* 20: 221 - 229.
- Schroeder J. L. and Hagiwara S. (1990). Repetitive increases in cytosolic  $\text{Ca}^{2+}$  of guard cells by abscisic acid activation of nonselective  $\text{Ca}^{2+}$  permeable channels. *Proceedings of the National Academy of Sciences in the USA* 87: 9305 - 9309.
- Schroeder J. L., Ward J. M. and Gassmann W. (1994). Perspectives on the physiology and structure of inward-rectifying  $\text{K}^+$  channels in higher plants: biophysical implications for  $\text{K}^+$  uptake. *Annual Review of Biophysics and Biomolecular Structure* 23: 441 - 471.
- Scott B. I. H. and Gulline H. F. (1975). Membrane changes in a circadian system. *Nature* 254: 69 - 70.



- Sehnke P. C. and Ferl R. J. (1996). Plant metabolism: enzyme regulation by 14-3-3 proteins. *Current Biology* 6: 1403 - 1405.
- Senn A. P. and Goldsmith M. H. M. (1988). Regulation of electrogenic proton pumping by auxin and fusicoccin as related to the growth of *Avena* coleoptiles. *Plant Physiology* 88: 131 - 138.
- Serrano E. E., Zeiger E. and Hagiwara S. (1988). Red light stimulates an electrogenic proton pump in *Vicia* guard cell protoplasts. *Proceedings of the National Academy of Sciences in the USA* 85: 436 - 440.
- Serrano R. (1989). Structure and function of plasma membrane ATPase. *Annual Review of Plant Physiology* 40: 61 - 94.
- Serrano R. (1990). Recent molecular approaches to the physiology of the plasma membrane proton pump. *Botanica Acta* 103: 230 - 234.
- Shimazaki K., Iino M. and Zeiger E. (1986). Blue light-dependent proton extrusion by guard cell protoplasts of *Vicia faba*. *Nature* 319: 324 - 326.
- Shinozaki K. and Yamaguchi-Shinozaki K. (1997). Gene expression and signal transduction in water-stress response. *Plant Physiology* 115: 327 - 334.
- Shirsat A. H., Bell A., Spence J. and Harris J. N. (1996 {a}). The *Brassica napus* extA gene is expressed in regions of the plant subject to tensile stresses. *Planta* 199: 618 - 624.
- Shirsat A. H., Wiczorek D. and Kozbial P. (1996 {b}). A gene for *Brassica napus* extensin is differentially expressed on wounding. *Plant Molecular Biology* 30: 1291 - 1300.
- Showalter A. M. (1993). Structure and function of plant cell wall proteins. *The Plant Cell* 5: 9 - 23.
- Skou J. (1975). The (Na<sup>+</sup> + K<sup>+</sup>) activated enzyme system and its relationship to transport of sodium and potassium. *Quarterly Review of Biophysics* 7: 401 - 434.
- Slayman C. L. (1974). Proton pumping and generalized energetics of transport. A review. In: *Membrane Transport in Plants* (edited by U. Zimmermann and J. Dainty). Springer-Verlag, Berlin, New York. pp. 107 - 119.
- Sovonick S. A., Geiger D. R. and Fellows R. J. (1974). Evidence for active phloem loading in the minor veins of sugar beet. *Plant Physiology* 54: 886 - 891.
- Spanswick R. M. (1981). Electrogenic ion pumps. *Annual Review of Plant Physiology* 32: 267 - 289.



Spill D. and Kaiser W. M. (1994). Partial purification of two proteins (100 kDa and 67 kDa) cooperating in the ATP-dependent inactivation of spinach leaf nitrate reductase. *Planta* 192: 183 - 188.

Starrach N. and Mayer W. E. (1989). Changes of the apoplastic pH and K<sup>+</sup> concentration in the *Phaseolus pulvinus in situ* in relation to rhythmic leaf movements. *Journal of Experimental Botany* 40: 865 - 873.

Steiner M. (1934). *Jahrb. Wiss. Botanik* 81: 94.

Stelter W. and Jeschke W. D. (1983). Potassium-sodium selectivity at the plasmalemma of cortical root cells and preferential release of sodium to the xylem vessels in roots of *Atriplex hortensis* cultivar Gelbe Gartenmelde. *Physiologia Plantarum* 58: 505 - 514.

Steudle E. (1989). Water flow in plants and its coupling to other processes: an overview. *Methods in Enzymology* 174: 183 - 225.

Steudle E. (1992). The biophysics of plant water: compartmentation, coupling with metabolic processes, and flow of water in plant roots. In: *Water and Life: Comparative Analysis of Water Relationships at the Organismic, Cellular, and Molecular Levels* (edited by G N. Somero, C. B. Osmond and C. L. Bolis). Springer-Verlag, Heidelberg. pp 173 - 204.

Steudle E. (1993). Pressure probe techniques: basic principles and application to studies of water and solute relations at the cell, tissue and organ level. In: *Water Deficits: Plant Responses from Cell to Community* (edited by J. A. C. Smith and H. Griffiths). Bios Scientific Publishers, Oxford, UK. pp 5 - 36.

Steudle E. (1994 {a}). The regulation of plant water at the cell, tissue, and organ level: role of active processes and of compartmentation. In: *Flux Control in Biological Systems. From Enzymes to Populations and Ecosystems* (edited by E. D. Schulze). Academic Press, San Diego. pp 237 - 299.

Steudle E. (1994 {b}). Water transport across roots. *Plant and Soil* 167: 79 - 90.

Steudle E. and Frensch J. (1996). Water transport in plants: role of the apoplast. *Plant and Soil* 187: 67 - 79.

Steudle E., Murrmann M. and Peterson C. A. (1993). Transport of water and solutes across maize roots modified by puncturing the endodermis. Further evidence for the composite transport model of the root. *Plant Physiology* 103: 335 - 349.

Steudle E. and Peterson A. (1998). How does water get through roots? *Journal of Experimental Botany* 49: 775 - 788.

Steudle E. and Zimmermann U. (1974). Turgor pressure regulation in algal cells: pressure-dependence of electrical parameters of the membrane in large pressure ranges.



In: *Membrane Transport in Plants* (edited by U. Zimmermann and J. Dainty). Springer-Verlag, Berlin, Heidelberg, New York. ISBN 3-540-06989-5. pp. 72 - 78.

Stickle W. B. and Ahokas R. (1974). The effects of tidal fluctuations of salinity on the provisional fluid composition of several echinoderms. *Comparative Biochemical Physiology* 47: 469 - 476.

Storey R., Pitman M. G. and Stelzer R. (1983). X-ray microanalysis of cells and cell compartments of *Atriplex spongiosa*. II. Roots. *Journal of Experimental Botany* 34: 1196 - 1206.

Storey R. and Wyn Jones R. G. (1979). Responses of *Atriplex spongiosa* and *Suaeda monoica* to salinity. *Plant Physiology* 63: 156 - 162.

Stumpf D. K. and O'Leary J. W. (1985). The distribution of Na<sup>+</sup>, K<sup>+</sup> and glycinebetaine in *Salicornia bigelovii*. *Journal of Experimental Botany* 36: 550 - 555.

Su W., Huber S. C. and Crawford N. M. (1996). Identification *in vitro* of a post-translational regulatory site in the hinge 1 region of *Arabidopsis* nitrate reductase. *The Plant Cell* 8: 519 - 527.

Sze H. (1985). H<sup>+</sup> translocating ATPase: advances using membrane vesicles. *Annual Review of Plant Physiology* 36: 175 - 208.

Teodoro A. E., Zingarelli L. and Lado P. (1998). Early changes of Cl<sup>-</sup> efflux and H<sup>+</sup> extrusion induced by osmotic stress in *Arabidopsis thaliana* cells. *Physiologia Plantarum* 102: 29 - 37.

Terry B. R., Findlay G. P. and Tyerman S. D. (1992). Direct effects of Ca<sup>2+</sup>-channel blockers on plasma membrane cation channels of *Amaranthus tricolor* protoplasts. *Journal of Experimental Botany* 43: 1457 - 1473.

Tetlow I. J. and Farrar J. F. (1993). Apoplastic sugar concentration and pH in barley leaves infected with brown rust. *Journal of Experimental Botany* 44: 929 - 936.

Tomos A. D. (1988). Cellular water relations of plants. In: *Water Science Review Volume 3* (edited by F. Franks). Cambridge University Press, Cambridge, UK. pp 186 - 277.

Tomos A. D. (1989). Turgor pressure and membrane transport. In: *Plant Membrane Transport: The Current Position* (edited by J. Dainty, M. I. De Michelis, E. Marré and F. Rasi-Caldogno). Elsevier, Amsterdam. ISBN 0-444-81328-4. pp. 559 - 562.

Tomos A. D., Hinde P., Richardson P., Prichard J. and Fricke W. (1994). Microsampling and measurements of solutes in single cells. In: *Plant Cell Biology - a Practical Approach* (edited by N. Harris and K. Oparka). IRL Press, Oxford, UK. ISBN 0-19-963399-1. pp 297 - 314.



- Tomos A. D. and Leigh R. A. (1999). The pressure probe: a versatile tool in plant cell physiology. *Annual Review of Plant Physiology and Plant Molecular Biology* 50: 447 - 472.
- Tomos A. D., Leigh R. A., Palta J. A. and Williams J. H. H. (1992). Sucrose and cell water relations. In: *Assimilate Partitioning Between and Within Organisms* (edited by C. J. Pollock and J. F. Farrar). Bios Scientific Publishers, Oxford. pp.71 - 89.
- Tomos A. D., Leigh R. A., Shaw C. A. and Wyn Jones R. G. (1984). A comparison of methods for measuring turgor pressures and osmotic pressures of cells of red beet storage root tissue. *Journal of Experimental Botany* 35: 1675 - 1683.
- Tomos A. D., Steudle E., Zimmermann U. and Schulze E. D. (1981). Water relations of leaf epidermal cells in *Tradescantia virginiana*. *Plant Physiology* 68: 1135 - 1143.
- Tomos A. D. and Wyn Jones R. G. (1988). Some transport properties of cells within tissues. In: *Solute Transport in Plant Cells and Tissues* (edited by D. A. Baker and J. L. Hall). Longman, Chichester, UK. ISBN 0-582-00580-9. pp 220 - 250.
- Tonomura Y. (1986). *Energy Transducing ATPases - Structure and Kinetics*. Cambridge University Press, Cambridge, UK.
- Tyree M. T. and Hammel H. T. (1972). The measurement of the turgor pressure and water relations of plants by the pressure-bomb technique. *Journal of Experimental Botany* 23: 267 - 282.
- Van Steveninck F. M. (1975). The "washing" or "aging" phenomenon in plant tissues. *Annual Review of Plant Physiology* 26: 237 - 258.
- Vance C. P., Kirk T. K. and Sherwood R. T. (1980). Lignification as a mechanism of disease resistance. *Annual Review of Plant Pathology* 18: 259 - 288.
- Wach A., Schlessler A. and Goffeau A. (1992). An alignment of 17 deduced protein sequences from plant, fungi, and protozoa H<sup>+</sup>-ATPase genes. *Journal of Bioenergetics and Biomembranes* 24: 309 - 317.
- Wainwright S. A., Biggs W. D., Currey J. D. and Gosline J. M. (1976). *Mechanical Design in Organisms*. Arnold Press, London. pp. 423.
- Wakil S. J., Stoops J. K. and Joshi V. C. (1983). Fatty acid synthesis and its regulation. *Annual Review of Biochemistry* 52: 537 - 579.
- Walderhaug M. O., Polarek J. W., Voelkner P., Daniel J. M., Hesse J. E., Altendorf K. and Epstein W. (1992). KdpD and KdpE, proteins that control expression of the kdpABC operon, are members of the two-component sensor-effector class of regulators. *Journal of Bacteriology* 174: 2152 - 2159.



- Walker N. A., Patrick J. W., Zang W. H. and Fieuw S. (1995). Efflux of photosynthate and acid from developing seed coats of *Phaseolus vulgaris* L.: a chemiosmotic analysis of pump-driven efflux. *Journal of Experimental Botany* 46: 539 - 549.
- Walter H. (1962). *Die Vegetation der Erde Vol. 1*. Jena.
- Watad A. A., Reuveni M., Bressan R. A. and Hasegawa P. M. (1991). Enhanced net  $K^+$  uptake capacity of NaCl-adapted cells. *Plant Physiology* 95: 1265 - 1269.
- Weatherly P. E. (1982). Water uptake and flow in roots. In: *Encyclopaedia of Plant Physiology, Volume 12B* (edited by O. L. Lange, P. S. Nobel, C. B. Osmond and H. Ziegler). Springer-Verlag, Berlin. pp 79 - 109.
- White P. J., Earnshaw M. J. and Clarkson D. T. (1991). Effects of growth and assay temperature on unidirectional  $K^+$  fluxes in roots of rye (*Secale cereale*). *Journal of Experimental Botany* 42: 1031 - 1041.
- Wiencke C., Gorham J., Tomos A. D. and Davenport J. (1992). Incomplete turgor adjustment in *Cladophora rupestris* under fluctuating salinity regimes. *Estuarine, Coastal and Shelf Science* 34: 413 - 427.
- Wolswinkel P. and Ammerlaan A. (1983). Phloem unloading in developing seeds of *Vicia faba* L. The effect of several inhibitors on the release of sucrose and amino acids by the seed coat. *Planta* 158: 205 - 215.
- Wu J. and Seliskar D. M. (1998). Salinity adaptation of plasma membrane  $H^+$ -ATPase in the salt marsh plant *Spartina patens*: ATP hydrolysis and enzyme kinetics. *Journal of Experimental Botany* 49: 1005 - 1013.
- Wyn Jones R. G. (1981). Salt tolerance. In: *Physiological Processes Limiting Plant Productivity* (edited by C. B. Johnson). Butterworths, London. pp 271 - 292.
- Wyn Jones R. G., Brady C. J. and Spiers J. (1979). Ionic and osmotic relations in plant cells. In: *Recent Advances in the Biochemistry of Cereals* (edited by D. L. Laidman and R. G. Wyn Jones). Academic Press, London, New York, San Francisco. pp 63 - 103.
- Wyn Jones R. G. and Gorham J. (1983). Osmoregulation. In: *Physiological Plant Ecology III. Responses to the Chemical Environment* (edited by O. L. Lange, P. S. Nobel, C. B. Osmond and H. Ziegler). Springer-Verlag, Berlin, Heidelberg, New York. pp 35 - 58.
- Wyn Jones R. G. and Pollard A. (1983). Proteins, enzymes and inorganic ions. In: *Encyclopaedia of Plant Physiology, New Series, Volume 15B* (edited by A. Lauchli and R. A. Bielecki). Springer-Verlag, Berlin, Heidelberg, New York. pp 651 - 681.



Wyn Jones R. G., Storey R., Leigh R. A., Ahmad N. and Pollard A. (1977 {a}). A hypothesis on cytoplasmic osmoregulation. In: *Regulation of Cell Membrane Activities in Plants* (edited by E. Marré and O. Ciferri). North-Holland Press, Amsterdam. pp 121 - 136.

Wyn Jones R. G., Storey R. and Pollard A. (1977 {b}). Ionic and osmotic regulation in plants, particularly halophytes. In: *Transmembrane Ionic Exchange in Plants* (edited by M. Thellier, A. Monnier, M. Demarty and J. Dainty). Colloques Internationaux CNRS, Paris. pp 537 - 544.

Wyse R. E., Zamski E. and Tomos A. D. (1986). Turgor regulation of sucrose transport in sugar beet taproot tissue. *Plant Physiology* 81: 478 - 481.

Xing T. L., Higgins V. J. and Blumwald E. (1996). Regulation of plant defence response to fungal pathogens: two types of protein kinase in the reversible phosphorylation of the host plasma membrane H<sup>+</sup>-ATPase. *The Plant Cell* 8: 555 - 564.

Yamauchi T., Nagata H. and Fujisawa H. (1981). A new activator protein that activates tryptophan 5-monooxygenase and tyrosine monooxygenase in the presence of Ca<sup>2+</sup>-calmodulin-dependent protein kinase: purification and characterization. *The Journal of Biological Chemistry* 256: 5404 - 5409.

Yeo A. R. (1974). Salt tolerance in the halophyte *Suaeda maritima* L. Dum. PhD Thesis. University of Sussex, UK.

Yeo A. R. (1981). Salt tolerance in the halophyte *Suaeda maritima* L. Dum.: intracellular compartmentation of ions. *Journal of Experimental Botany* 32: 487 - 497.

Yeo A. R. (1983). Salinity resistance - physiologies and prices. *Physiologia Plantarum* 8: 214 - 222.

Yeo A. R. and Flowers T. J. (1980). Salt tolerance in the halophyte *Suaeda maritima* L. Dum.: evaluation of the effect of salinity upon growth. *Journal of Experimental Botany* 31: 1171 - 1183.

Yeo A. R. and Flowers T. J. (1986). Ion transport in *Suaeda maritima*: its relation to growth and implications for the pathway of radial transport of ions across the root. *Journal of Experimental Botany* 37: 143 - 159.

Ze-Sheng L. and Delrot S. (1987). Osmotic dependence of the transmembrane potential difference of broad bean mesocarp cells. *Plant Physiology* 84: 895 - 899.

Zeiger E. (1983). The biology of stomatal guard cells. *Annual Review of Plant Physiology* 34: 441 - 475.

Zimmermann U. (1977). Cell turgor regulation and pressure mediated transport processes. In: *Integration of Activity in the Higher Plant* (edited by D. Jennings).



- Proceedings of the 31<sup>st</sup> symposium of the Society for Experimental Biology. Cambridge University Press. pp. 117 - 154.
- Zimmermann U. (1978). Physics of turgor and osmoregulation. *Annual Review of Plant Physiology* 29: 121 - 148.
- Zimmermann U., Beckers F. and Steudle E. (1977). Turgor sensing in plant cells by the electromechanical properties of the membrane. In: *Transmembrane Ionic Exchange in Plants* (edited by M. Thellier). CNRS, Paris. pp. 155 - 165.
- Zimmermann U., Haase A., Langbein D. and Meinzer F. (1993). Mechanisms of long-distance water transport in plants: a re-examination of some paradigms in the light of new evidence. *Philosophical Transactions of the Royal Society of London Series B* 341: 19 - 31.
- Zimmermann U., Meinzer F. C., Benkert R., Zhu J. J., Schneider H., Goldstein G., Kuchenbrod E. and Haase A. (1994 {a}). Xylem water transport: is the available evidence consistent with the cohesion theory? *Plant, Cell and Environment* 17: 1169 - 1181.
- Zimmermann U., Meinzer F. and Bentrup F. W. (1995). How does water ascend in tall trees and other vascular plants? *Annals of Botany* 76: 545 - 551.
- Zimmermann U., Pilwat G. and Riemann F. (1974). Dielectric breakdown in cell membranes. *The Biophysical Journal* 14: 881 - 899.
- Zimmermann U., Rygol J., Balling A., Klock G., Metzler A. and Haase A. (1992). Radial turgor and osmotic pressure profiles in intact and excised roots of *Aster tripolium*. Pressure probe measurements and nuclear magnetic resonance-imaging analysis. *Plant Physiology* 99: 186 - 196.
- Zimmermann U. and Steudle E. (1971). Effects of potassium concentration and osmotic pressure of sea water on the cell turgor pressure of *Chaetomorpha linum*. *Marine Biology* 11: 132 - 137.
- Zimmermann U. and Steudle E. (1974). The pressure dependence of the hydraulic conductivity, the membrane resistance and membrane potential during turgor pressure regulation in *Valonia utricularis*. *Journal of Membrane Biology* 16: 331 - 352.
- Zimmermann U., Zhu J. J., Meinzer F. C., Goldstein G., Schneider H., Zimmermann G., Benkert R., Thürmer F., Melcher P., Webb D. and Haase A. (1994 {b}). High molecular weight organic compounds in the xylem sap of mangroves: implications for long distance water transport. *Botanica Acta* 107: 218 - 229.